Sharp imaging of Multiple object pointS: How and Why

P. Benítez[1,2], J.C.Miñano[1,2], M. Nikolic[1],
L. Jiayao[1], J.M. Infante[1] , F. Duerr[3]

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Abstract:

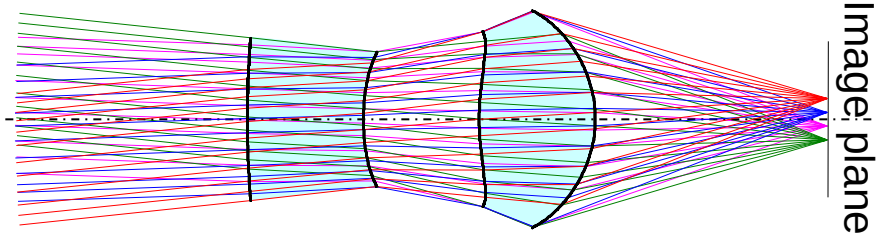
- Is it possible to sharply image M object points with N surfaces when N < M?
- Under what conditions?
- Why is it interesting for optimization?
- What is the role of the SMS method?

Answers will be given!

SMS method

Usually presented as a method to couple N wavefront pairs with N surfaces

SMS 2D

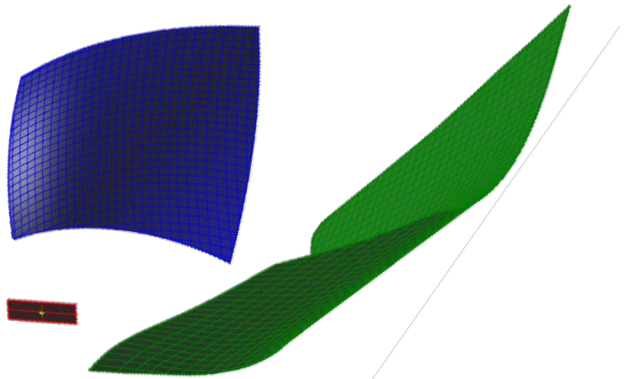


~~4~~ 6

Up to ~~4~~ 6 aspheres

J.C. Miñano et al., Optics Express, Volume 17, 2009

SMS 3D



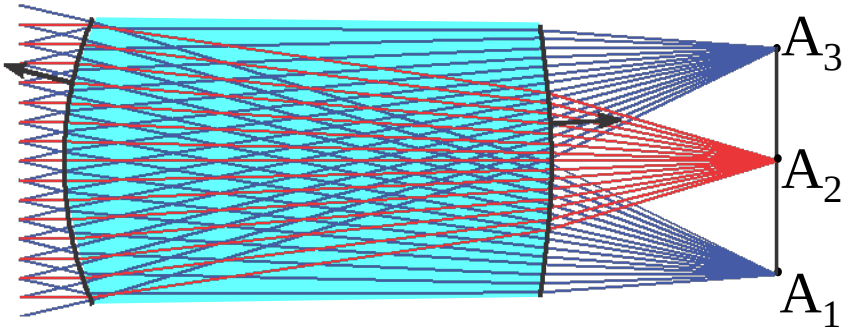
Up to 2 free-forms

P. Benítez et al., Optical Engineering, 2003

SMS method

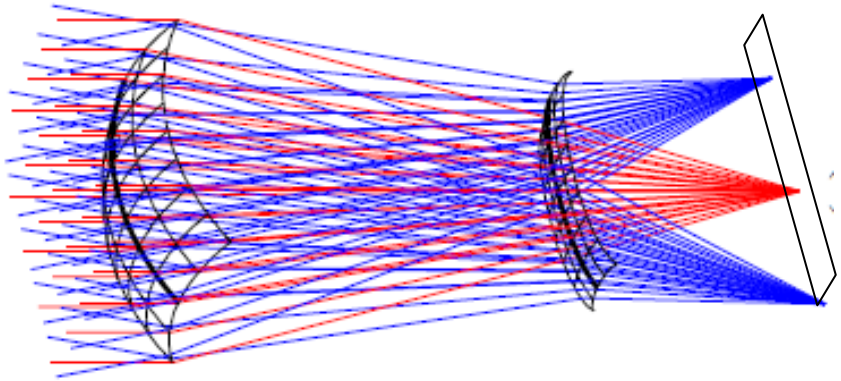
However, recent findings seem contradictory

SMS 2D



F. Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Opt.Express 20, 5576–5585, (2012)

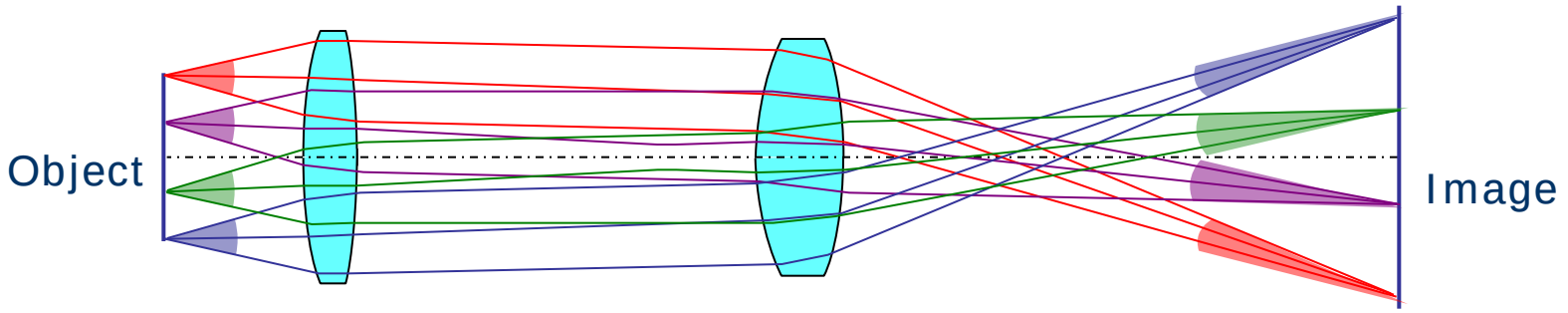
SMS 3D



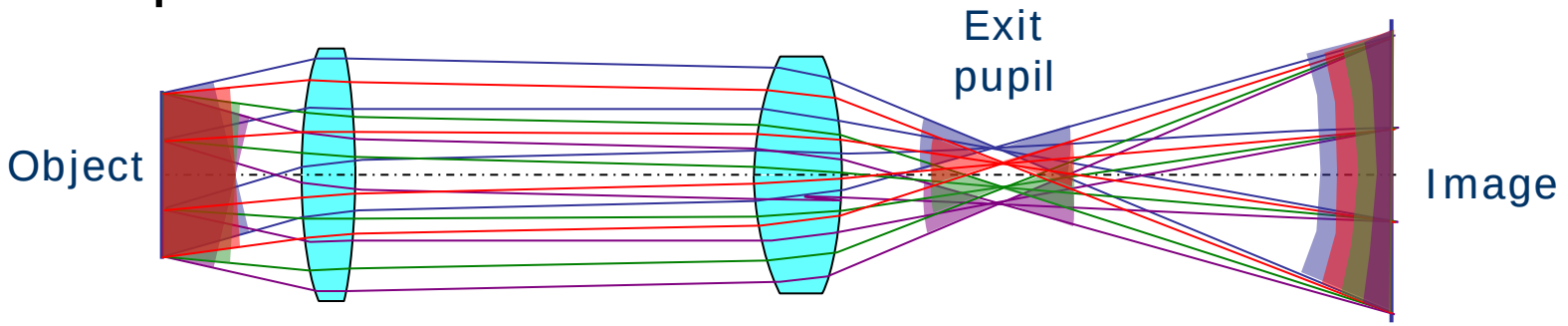
F. Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Optics Express 20, 10839–10846, (2012)

Object versus Pupil discretization

- Object discretization



- Pupil discretization



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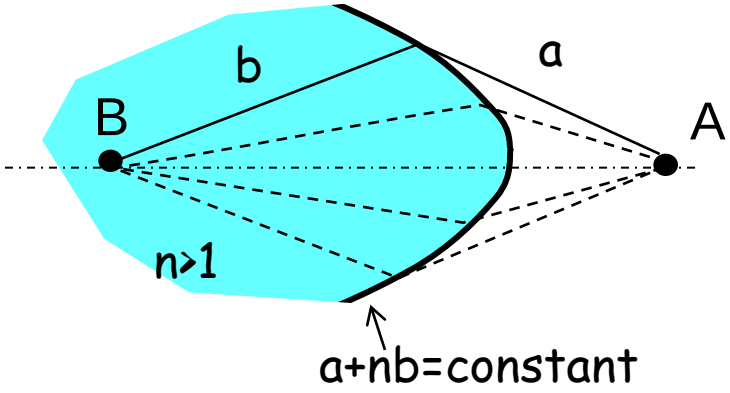
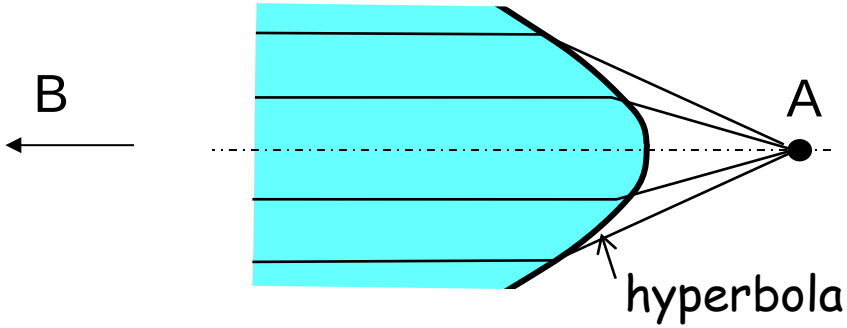
- Facing the general case
- Application to optimization
- Conclusions

Early work

Cartesian ovals





R. Descartes, "Géométrie", Leyden (1637)

These are 2D and 3D solutions

Early work

On the problem of ideal flux concentrators

W. T. Welford
Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
R. Winston
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 28 September 1977)

one of these for rays incident above the axis and the other for rays incident below the axis, and this is impossible. Thus in general it is not possible to correct a system with a finite number of surfaces for meridian rays to one off-axis object point, much less for skew rays. There are well-known exceptions to this, namely, systems of spherical symmetry such

(1977)

Early work

On the problem of ideal flux concentrators: Addendum

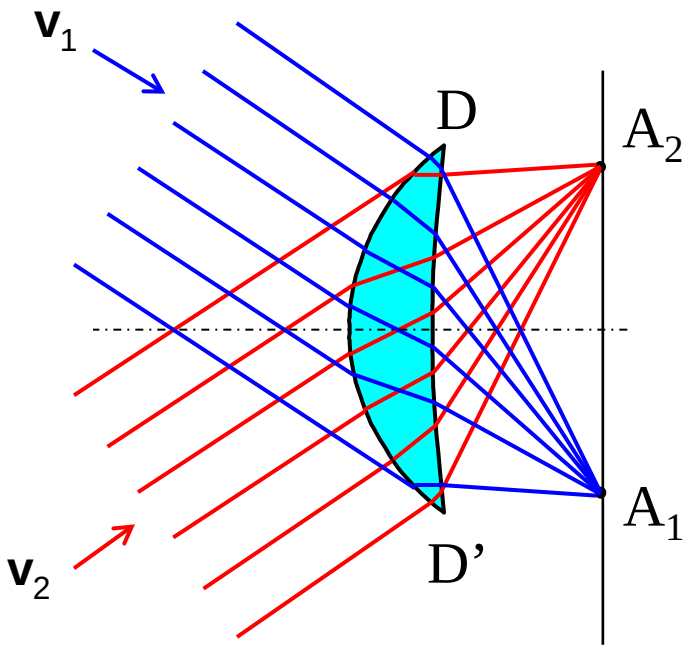
W. T. Welford
Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
R. Winston
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 13 September 1978; revised 3 November 1978)

and so on. But we have only a finite number n of surfaces available, so that only $n - 1$ one-dimensional fans of rays can come to a point focus, not the full two-dimensional array in the pupil.

(1978)

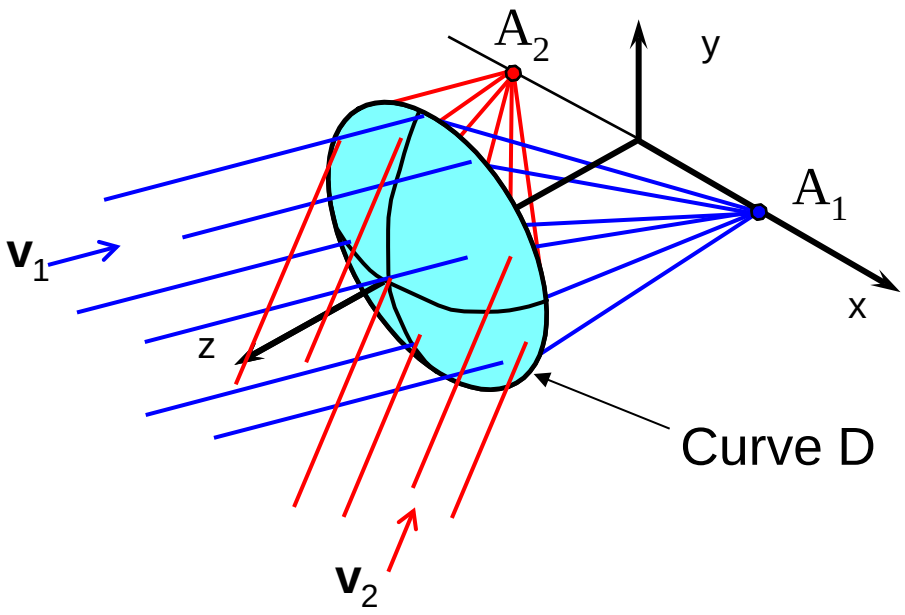
First SMS designs

In 2D



J.C. Miñano, J.C. Glez,
Appl. Opt. 31 (16), 1992

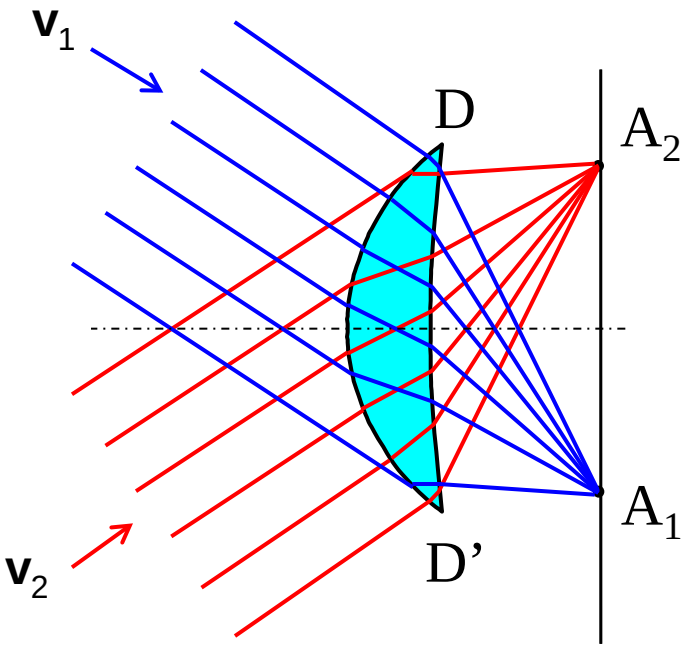
In 3D



P. Benítez, R. Mohedano, J.C. Miñano,
SPIE Vol. 3781, 1999

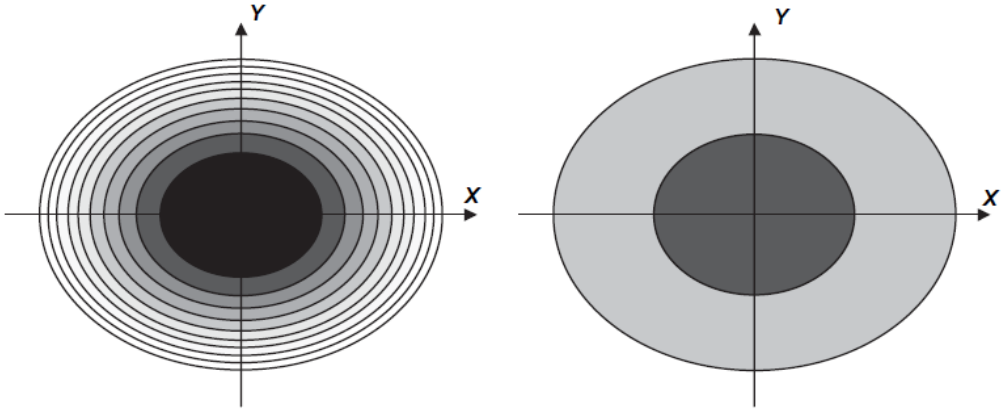
First SMS designs

In 2D



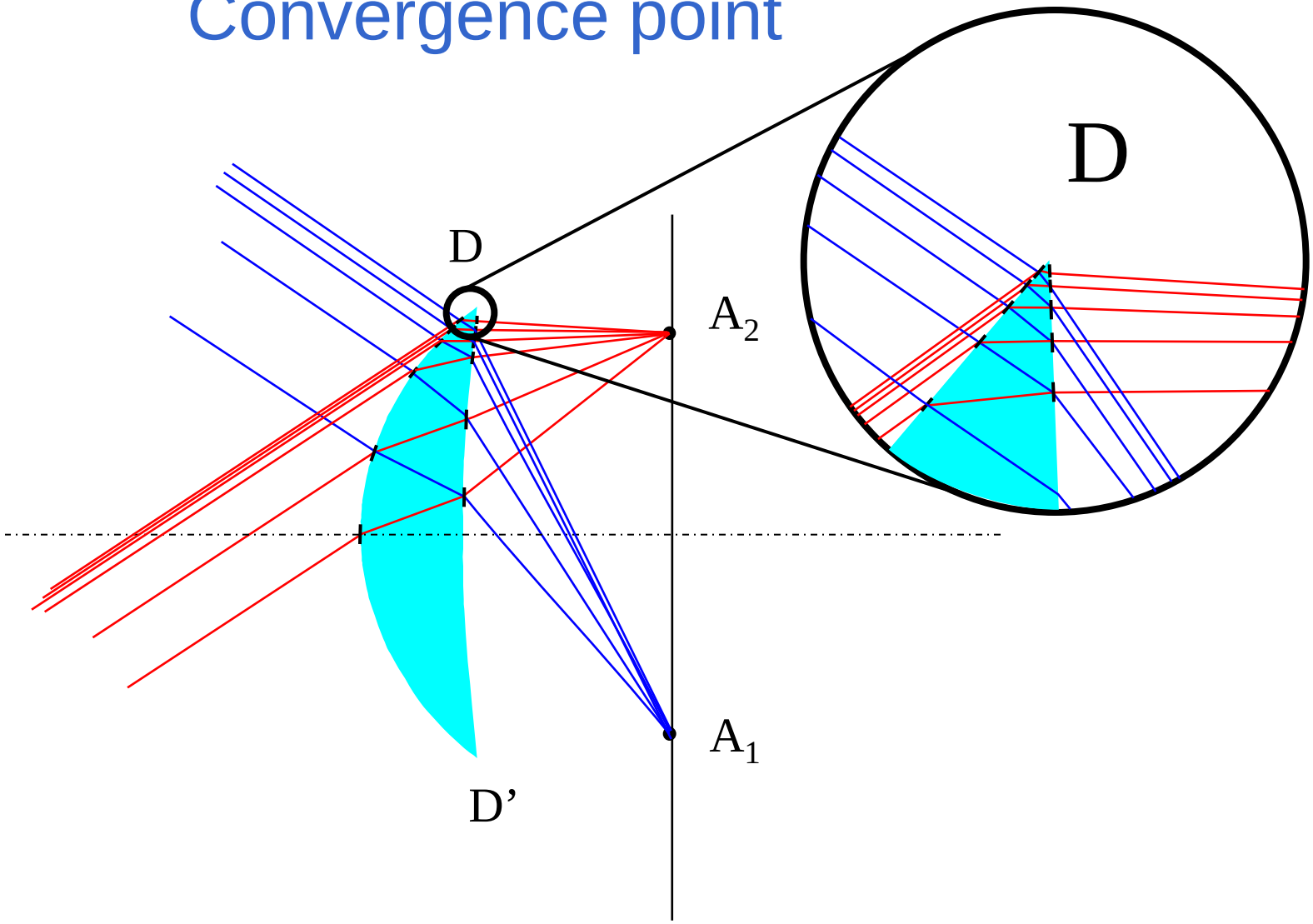
J.C. Miñano, J.C. Glez,
Appl. Opt. 31 (16), 1992

In 3D

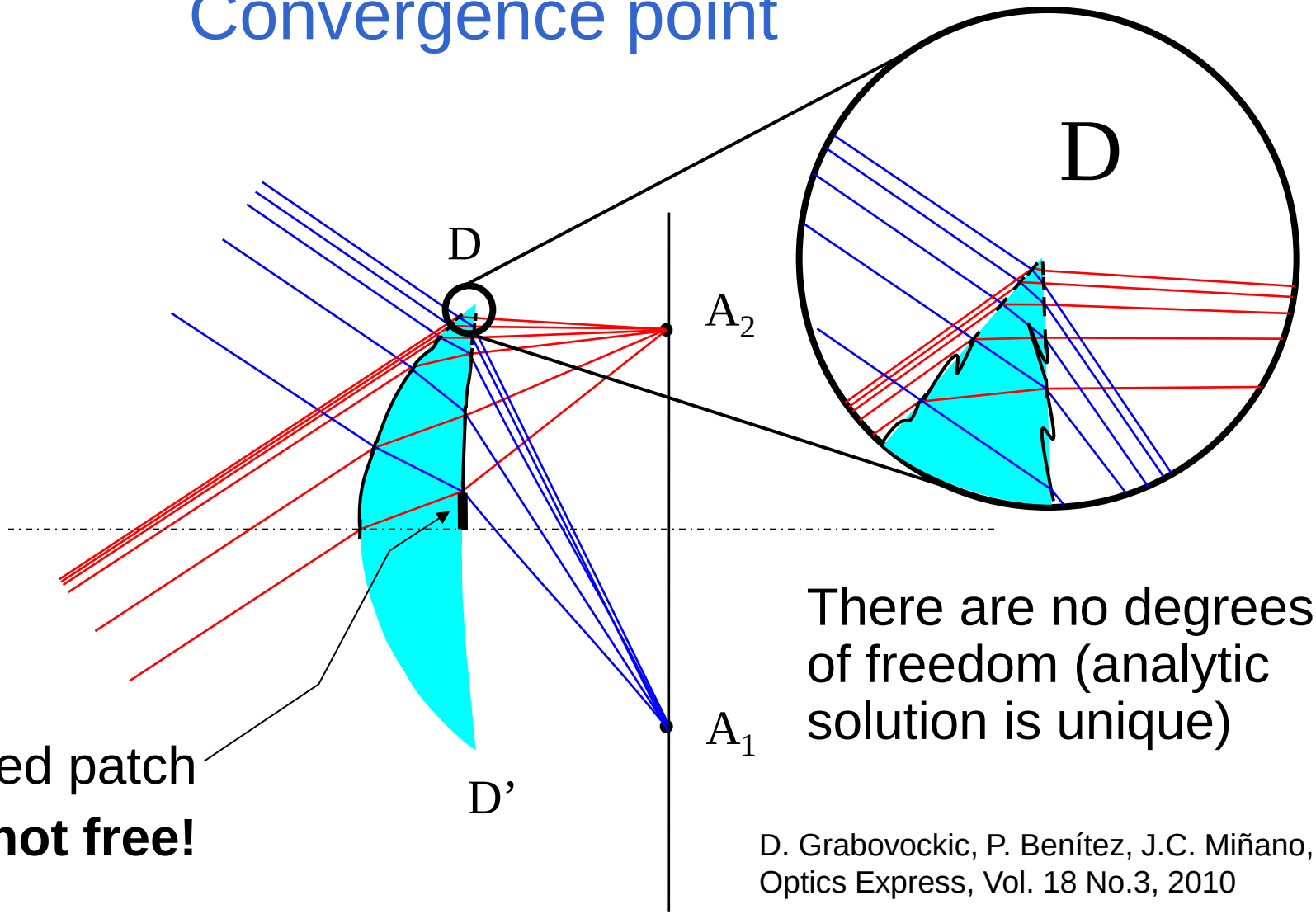


P. Benítez, R. Mohedano, J.C. Miñano,
SPIE Vol. 3781, 1999

Convergence point



Convergence point



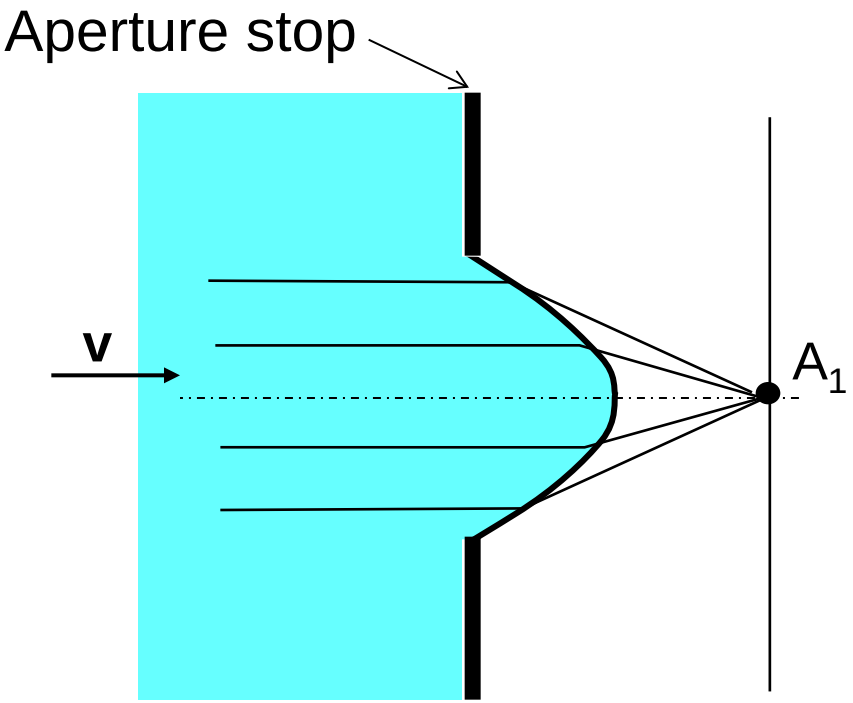
Seed patch

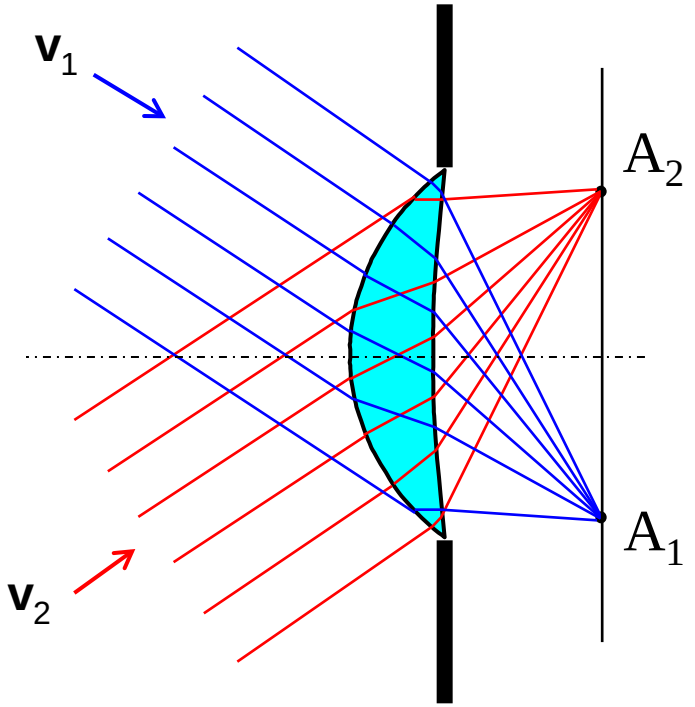
is not free!

There are no degrees of freedom (analytic solution is unique)

D. Grabovockic, P. Benítez, J.C. Miñano, Optics Express, Vol. 18 No.3, 2010

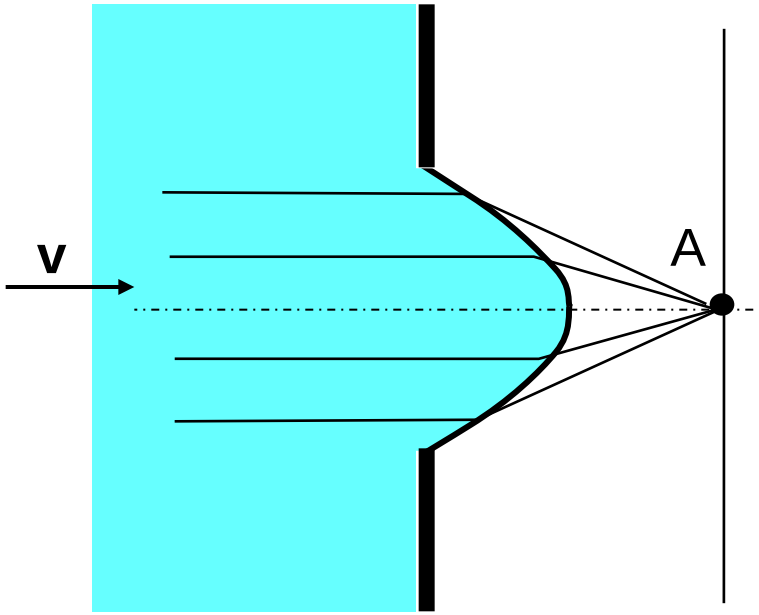
Similarities

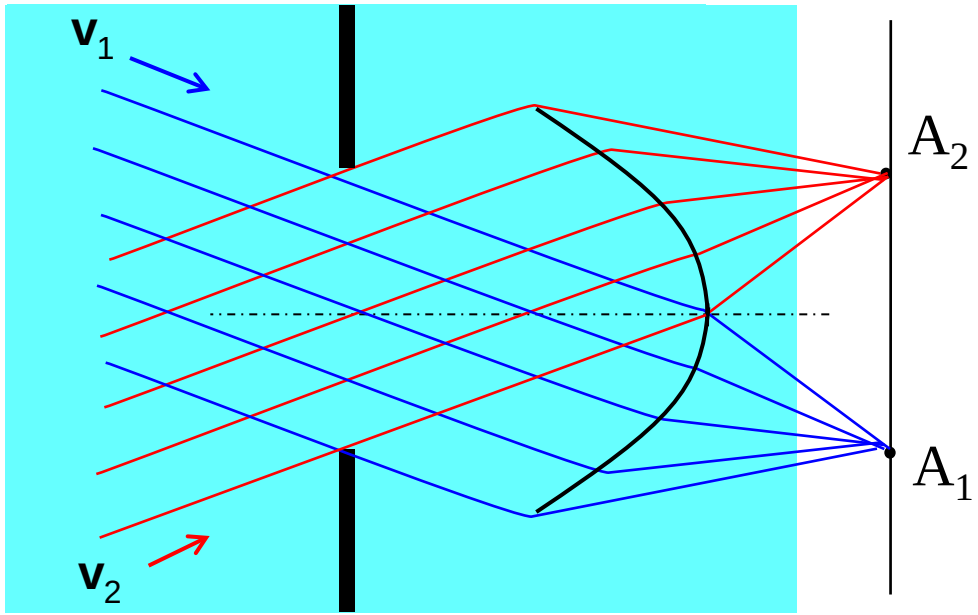




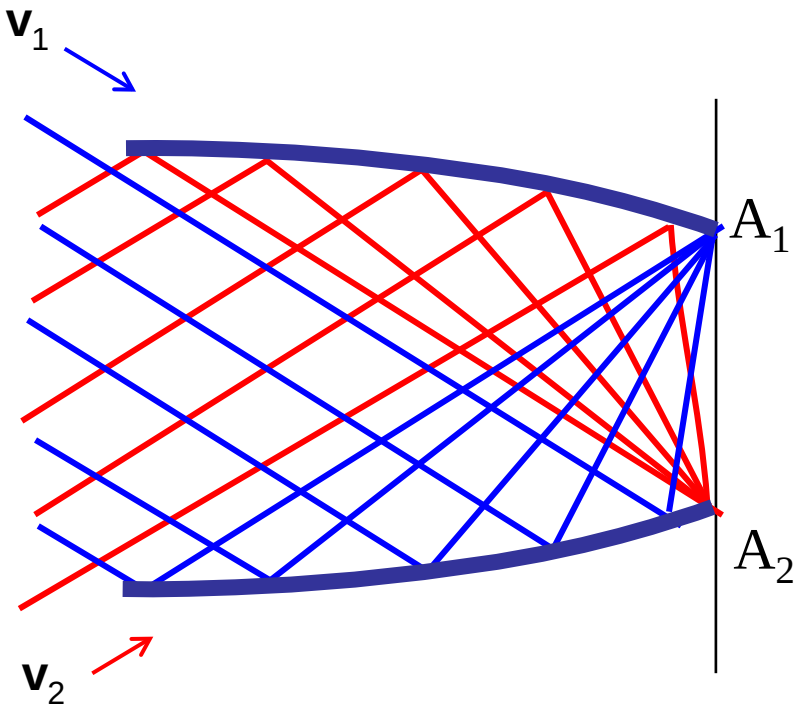
- All surfaces are at the aperture stop
- Both are unique solutions
- Number of object points = Number of surfaces

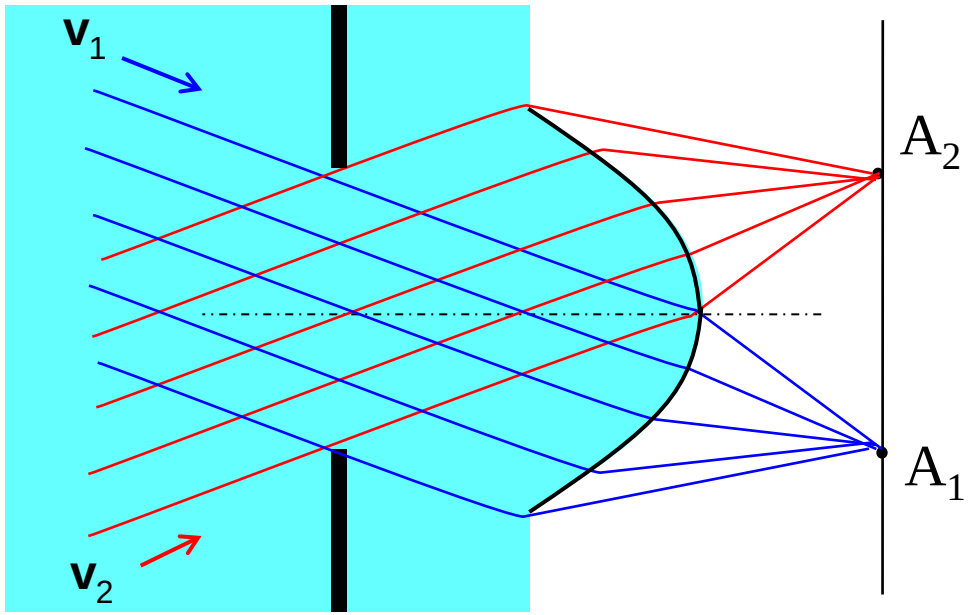
One surface, two object points





One surface, two object points





Early works

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W. T. Welford
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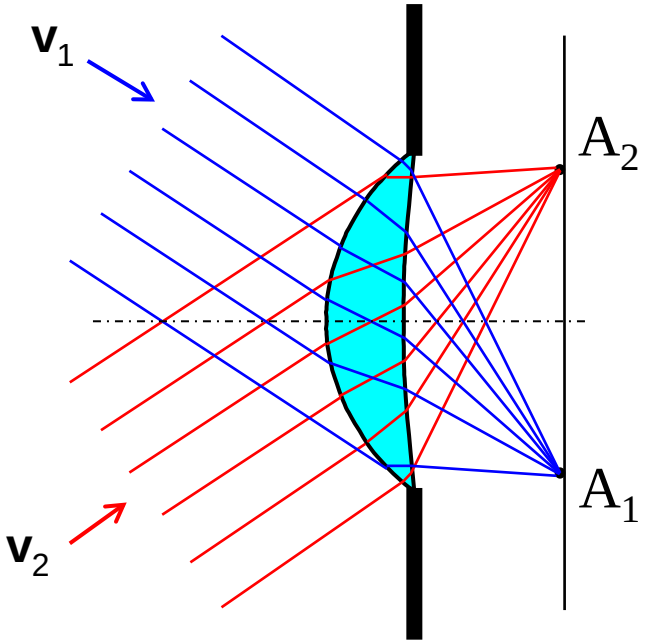
a clue to another solution: if we have a surface in the system so placed that all the rays meet it on one side only of the axis, i.e., very remote from the aperture stop in ordinary lens design language, then this surface does not have to satisfy contradictory conditions and the edge-ray condition can be satisfied.

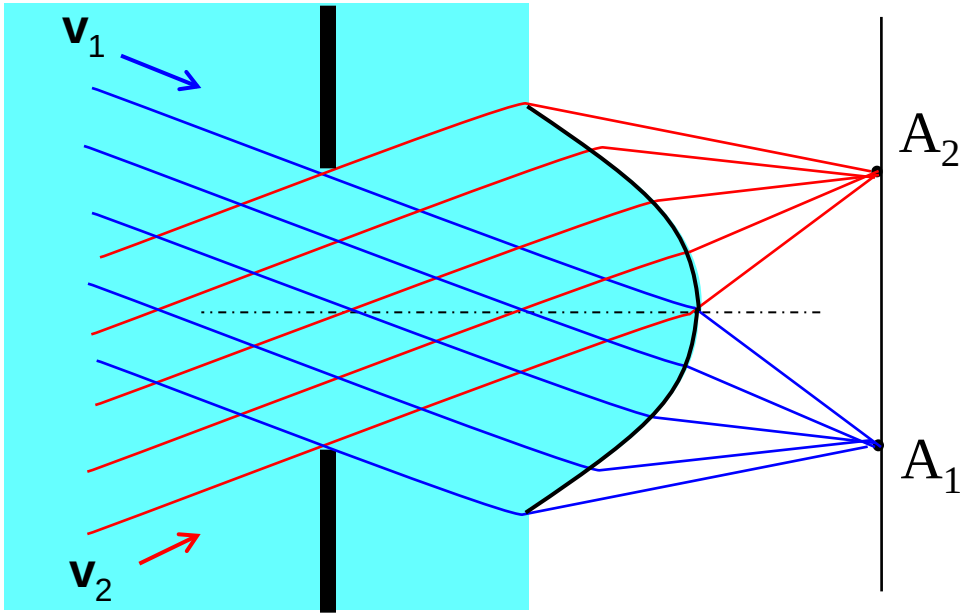
(1977)

Comparison

- Surfaces = beam print
- Two refractions

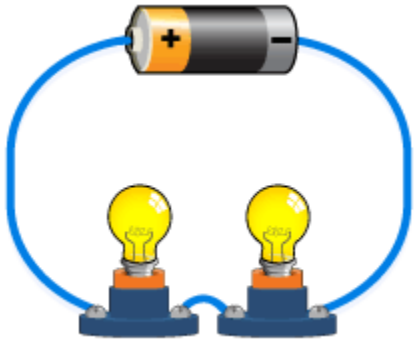


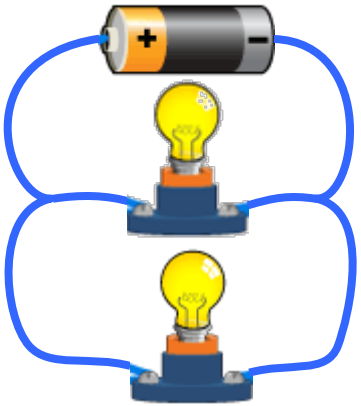
- Surface = 2 x beam print
- Single refraction

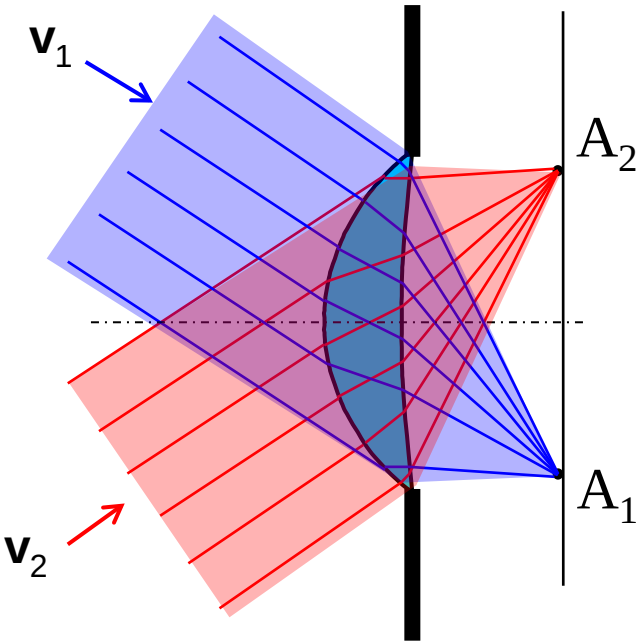


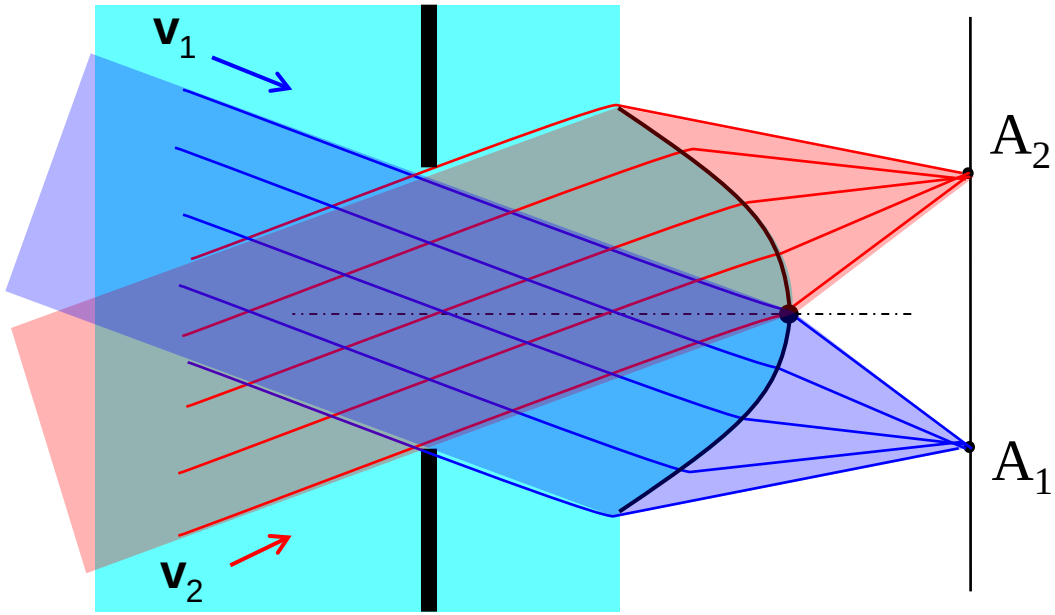
In both cases solutions are unique

Comparison









Both cases can be also seen as two surfaces sharing one edge

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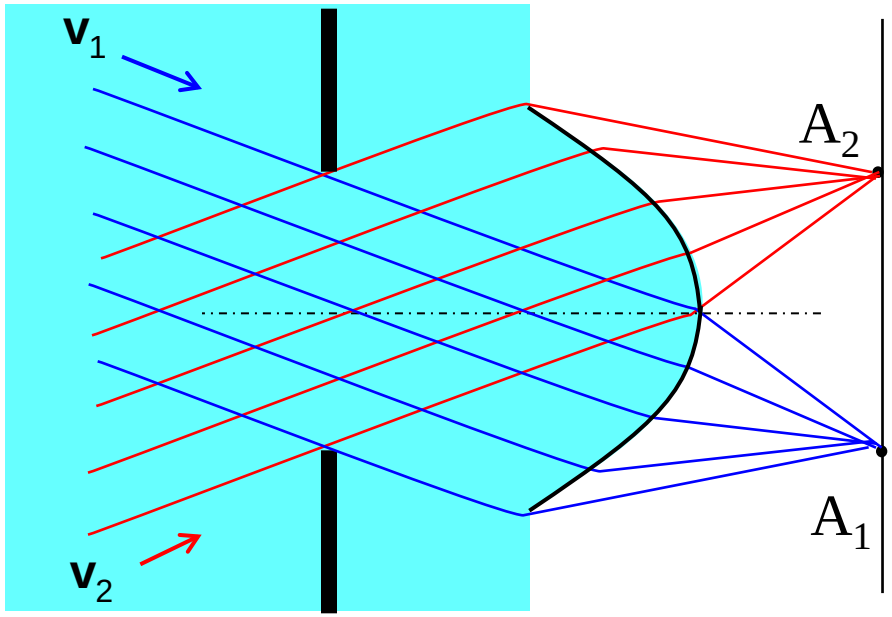
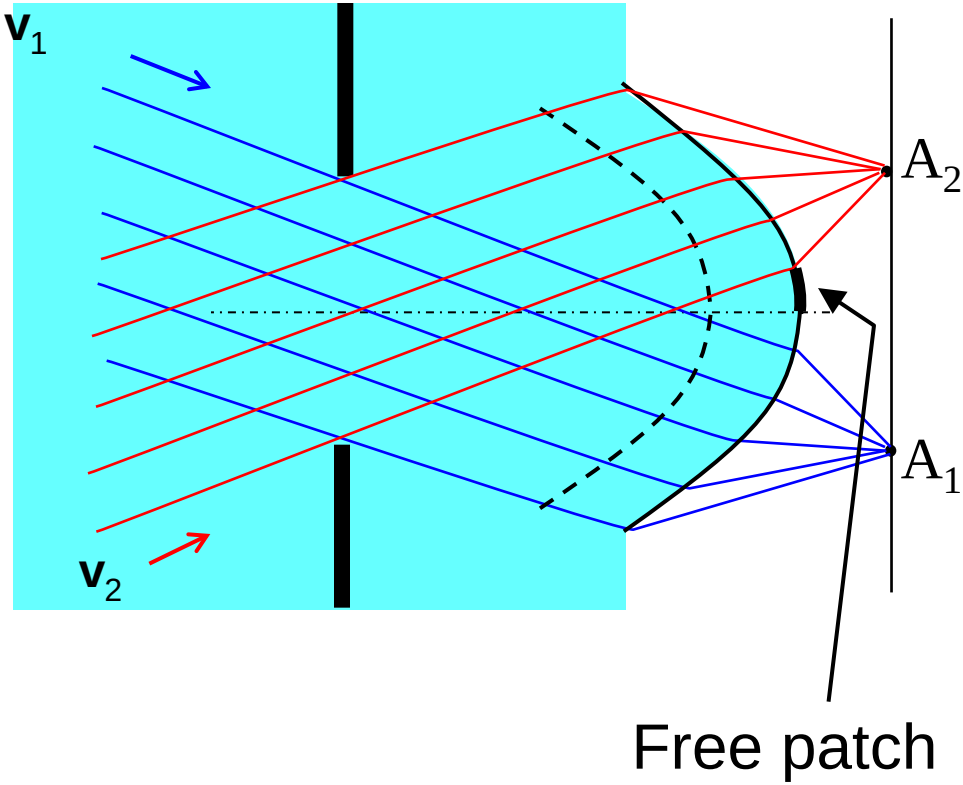
Increasing paralelism





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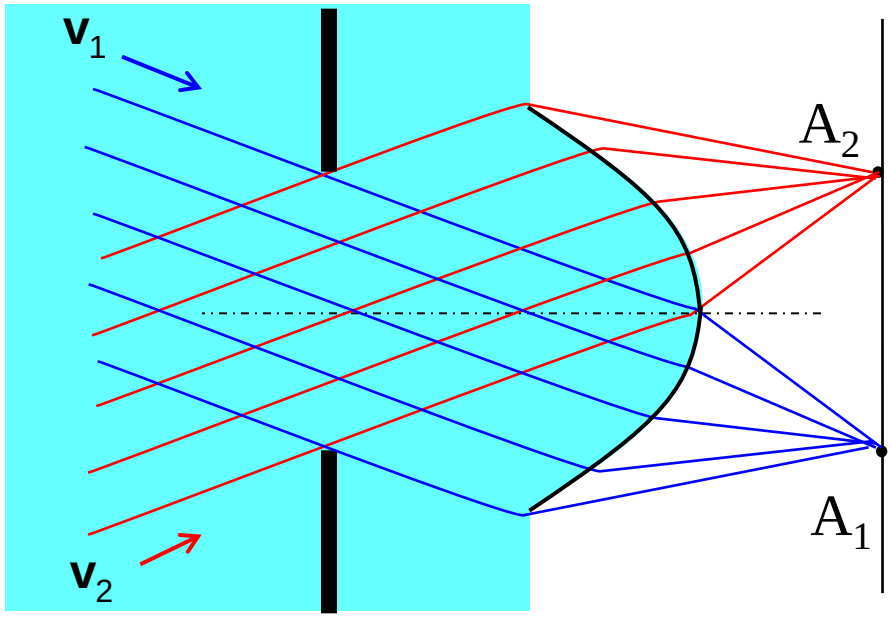
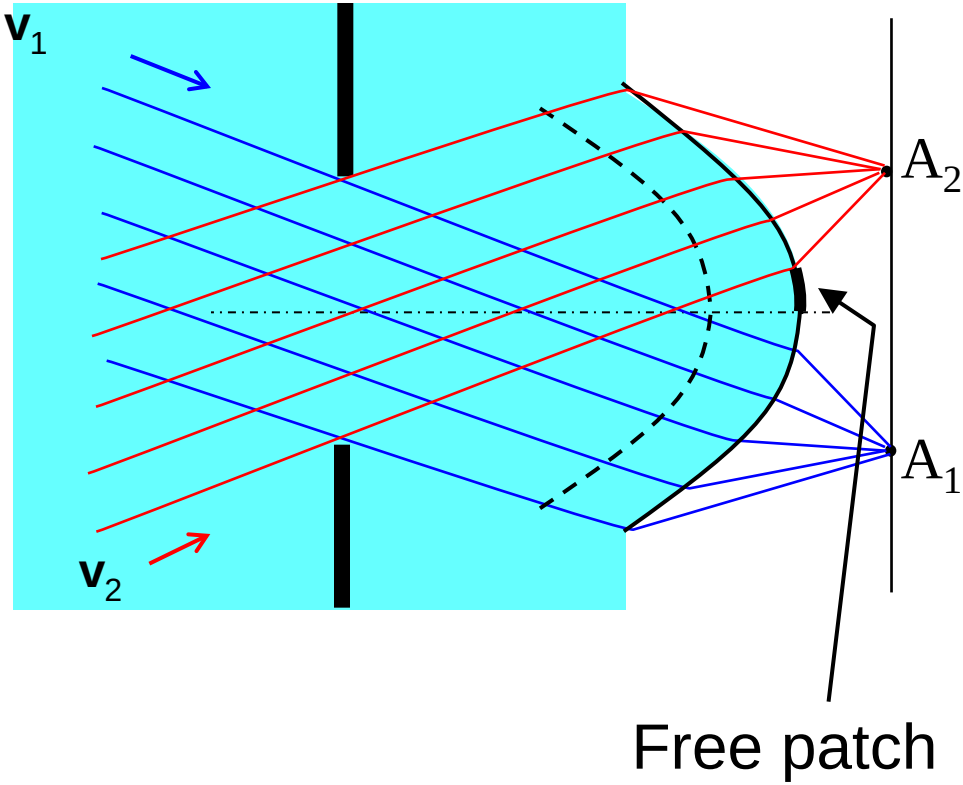
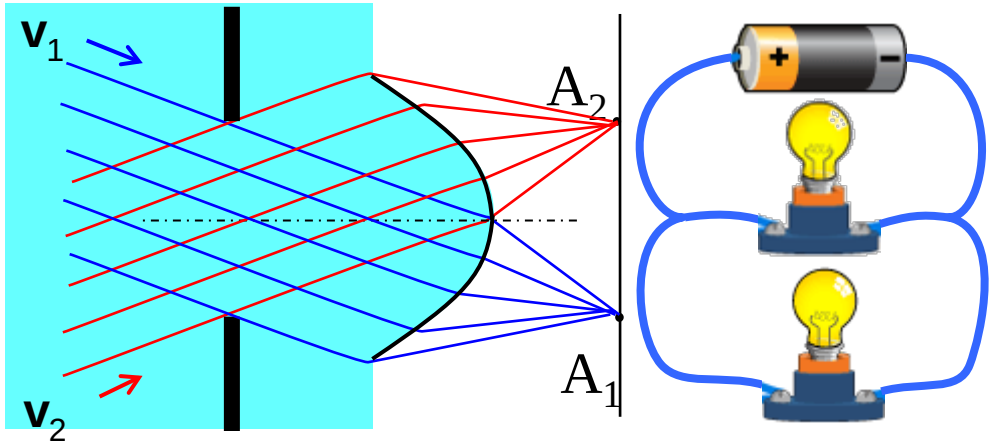
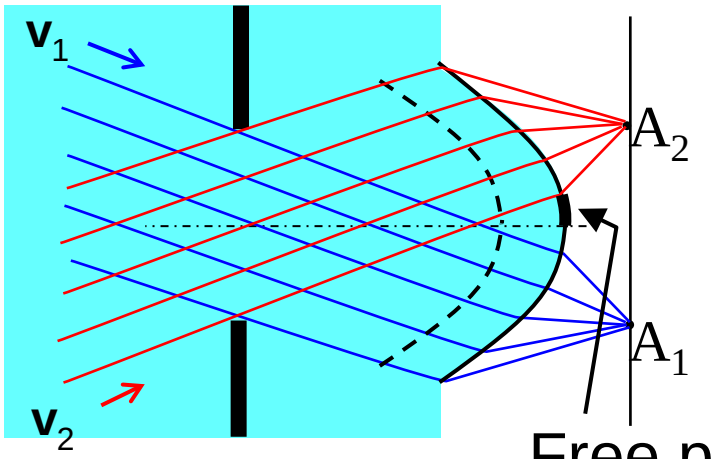




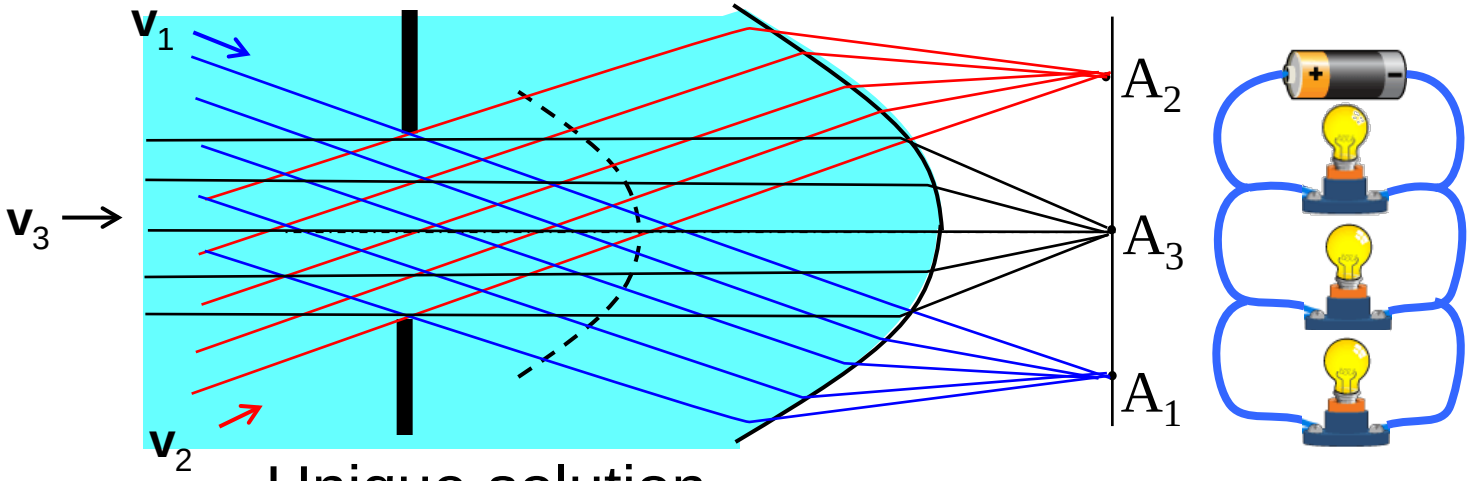
Transition from two to three object points



Unique solution

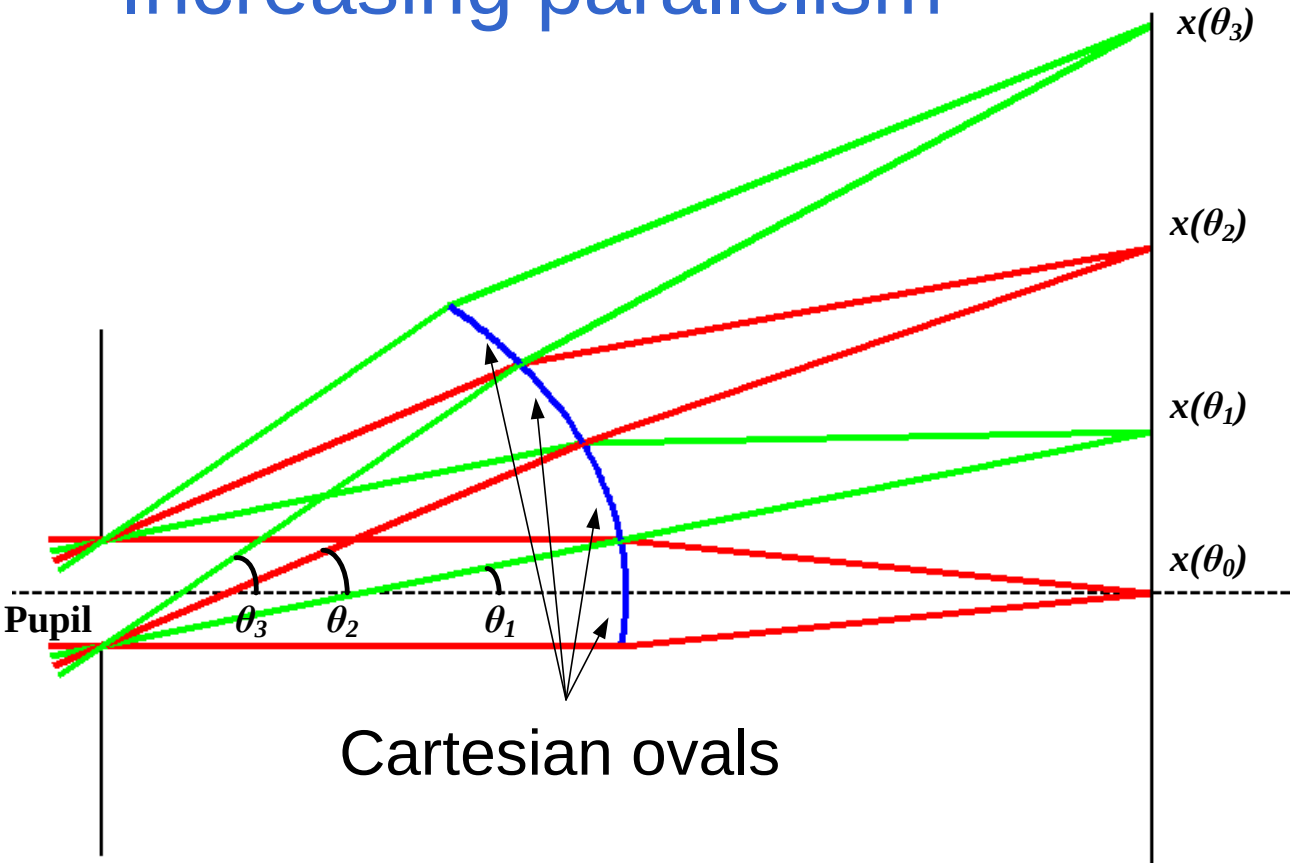


Free patch



Unique solution

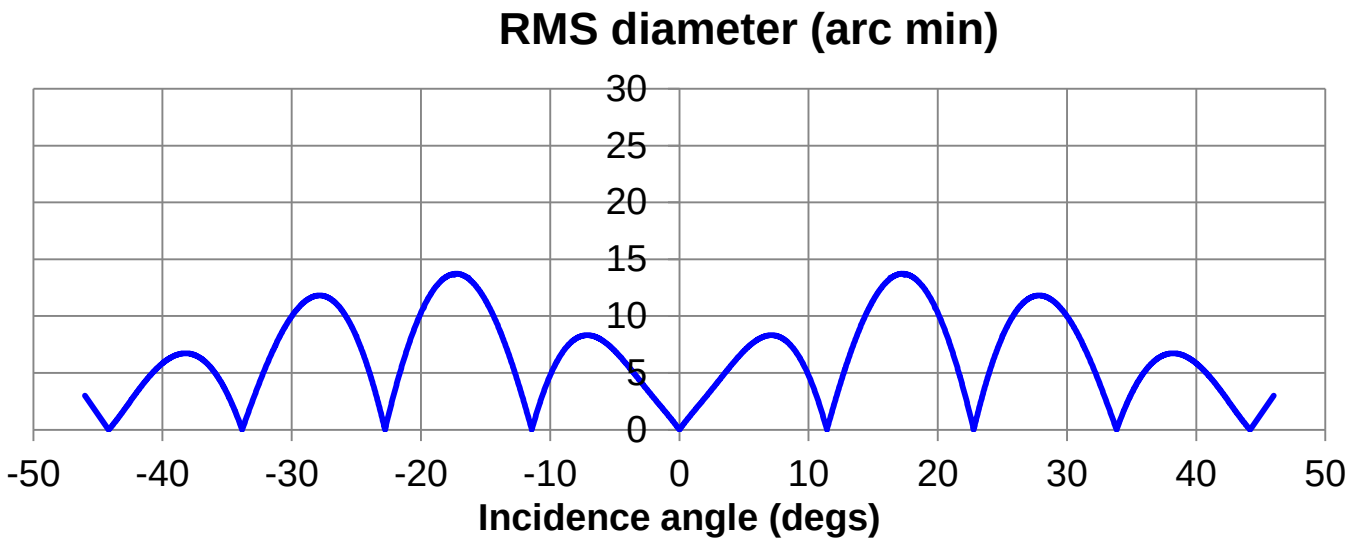
Increasing parallelism



Cartesian ovals

L. Jiayao, P. Benítez, J.C. Miñano, SPIE Vol 8550, 2012

One surface, 10 object points



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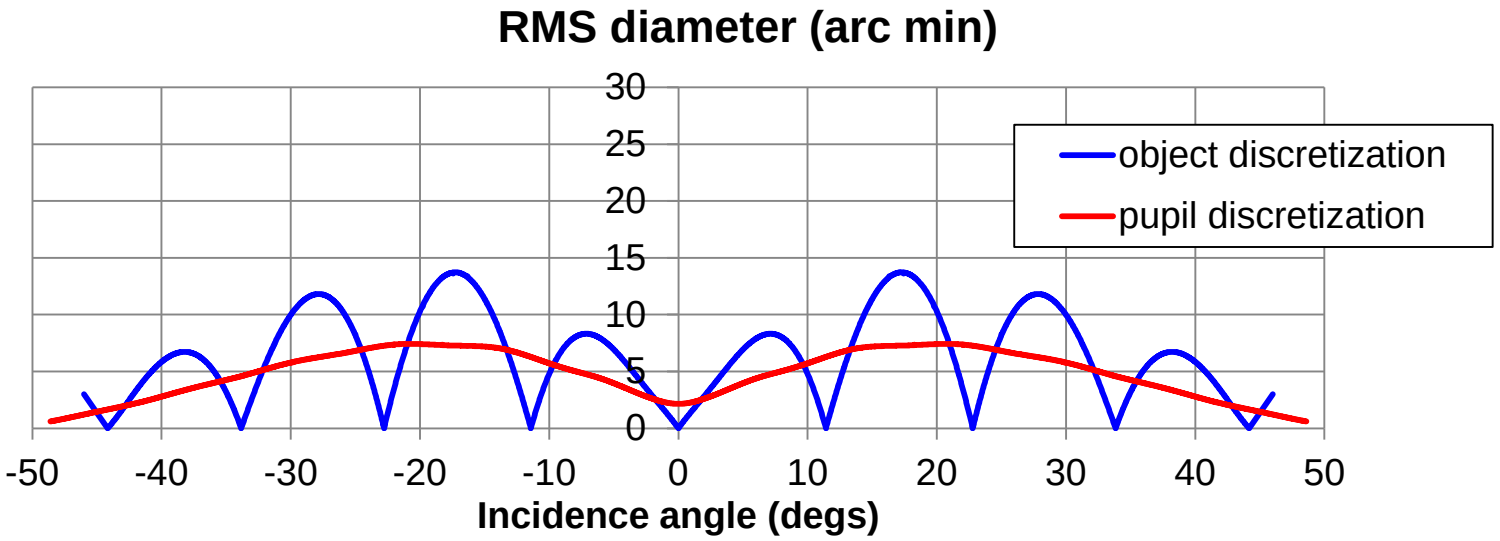
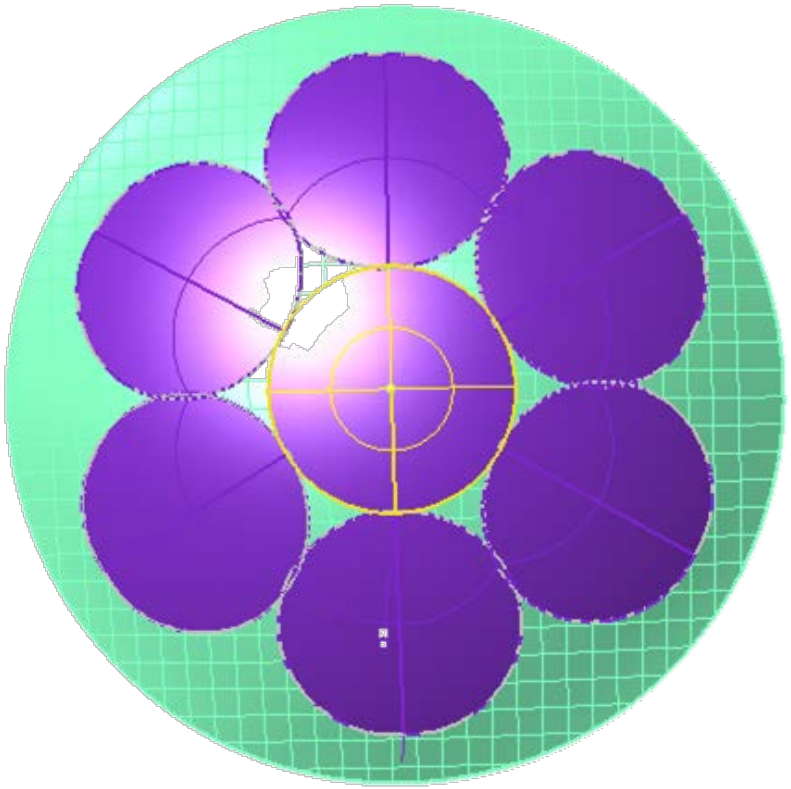
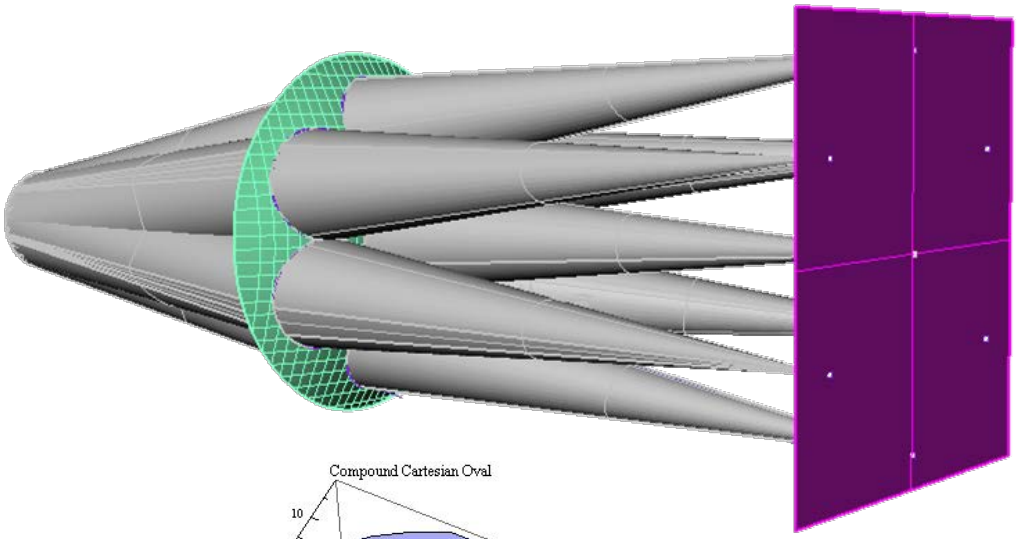
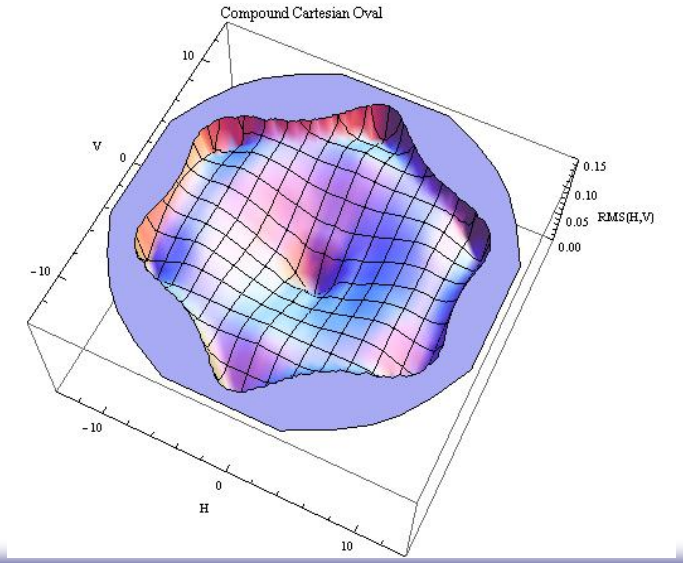


L. Jiayao, P. Benítez, J.C. Miñano, SPIE Vol 8550, 2012

Also in 3D



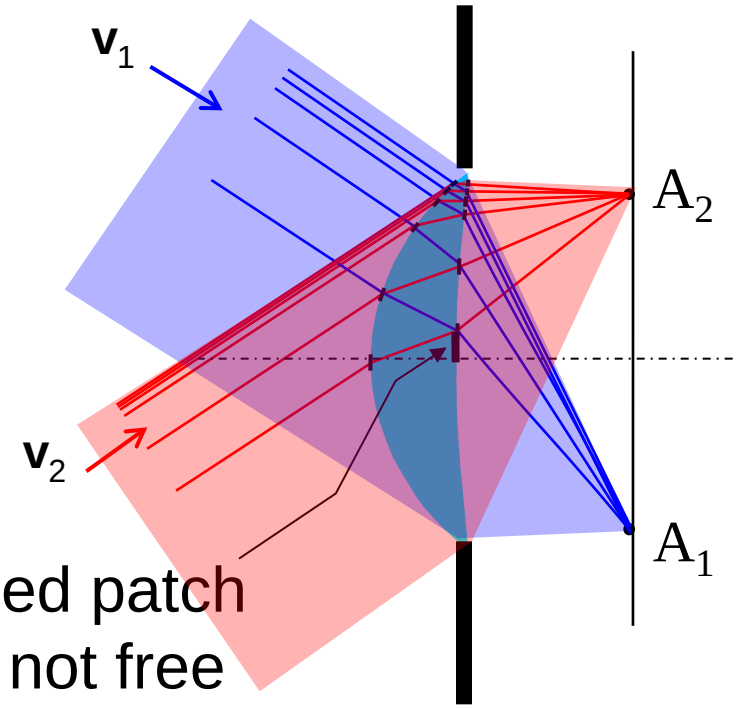




P. Benítez, J.C. Miñano, M. Nikolic,
L. Jiayao , J.M. Infante, F. Duerr
OSA Freeform meeting, November 2013

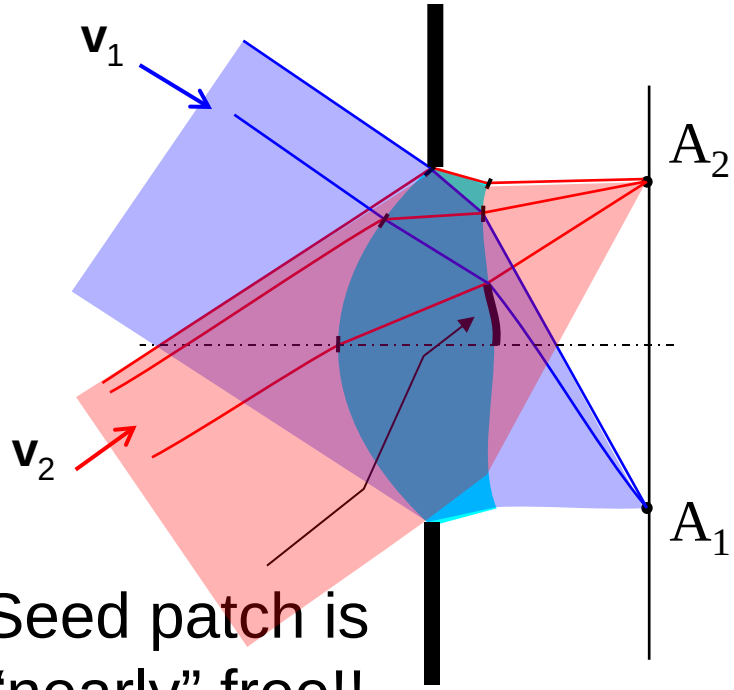
Series-parallel combinations

SMS thicker lenses do not have convergence points



Seed patch is not free

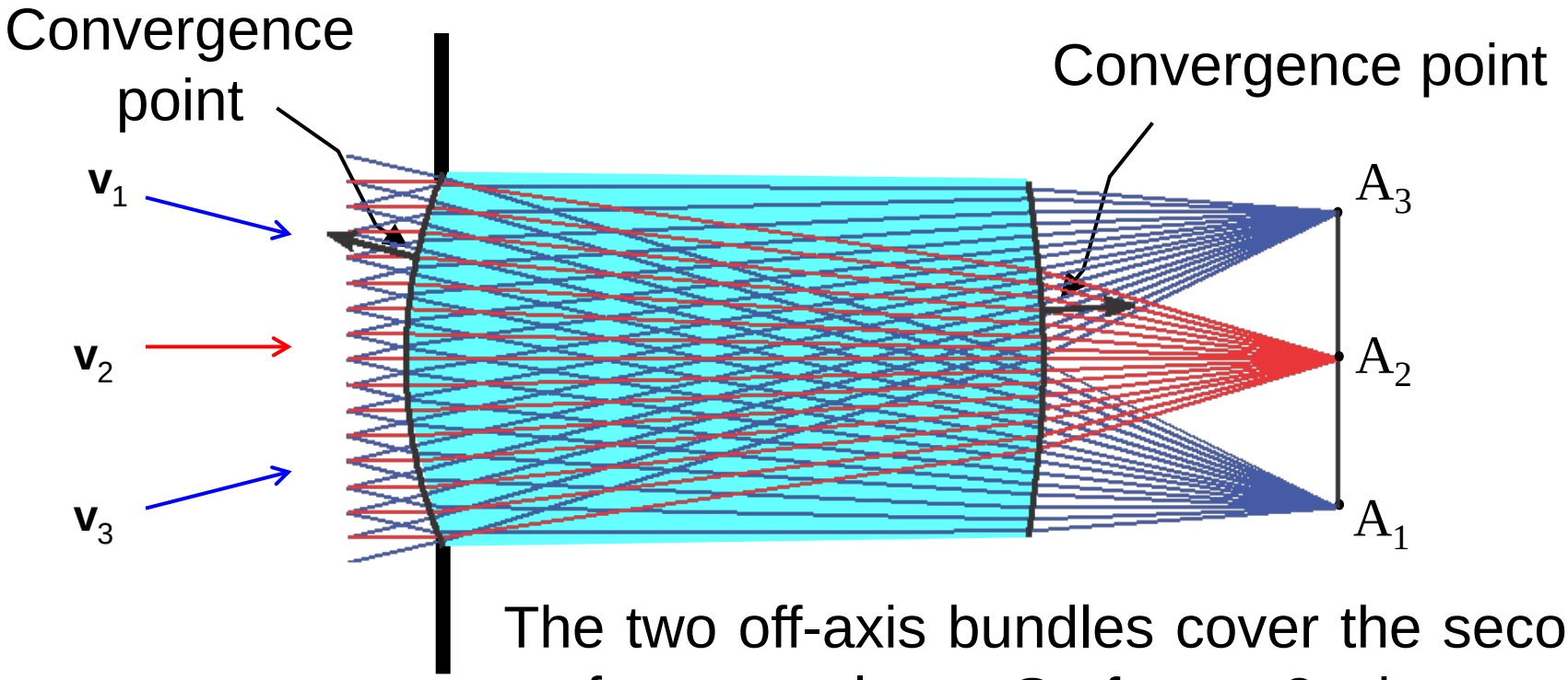
J.C. Miñano, J.C. Glez,
Appl. Opt. 31 (16), 1992



Seed patch is "nearly" free!!

F. Muñoz P. Benitez, J.C. Miñano,
SPIE Vol. 7061A 2008

Two surfaces, three object points

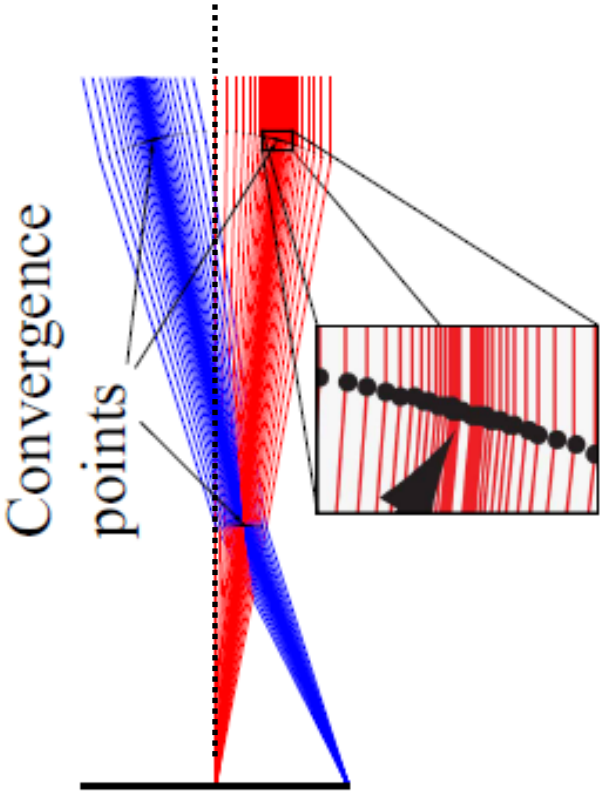


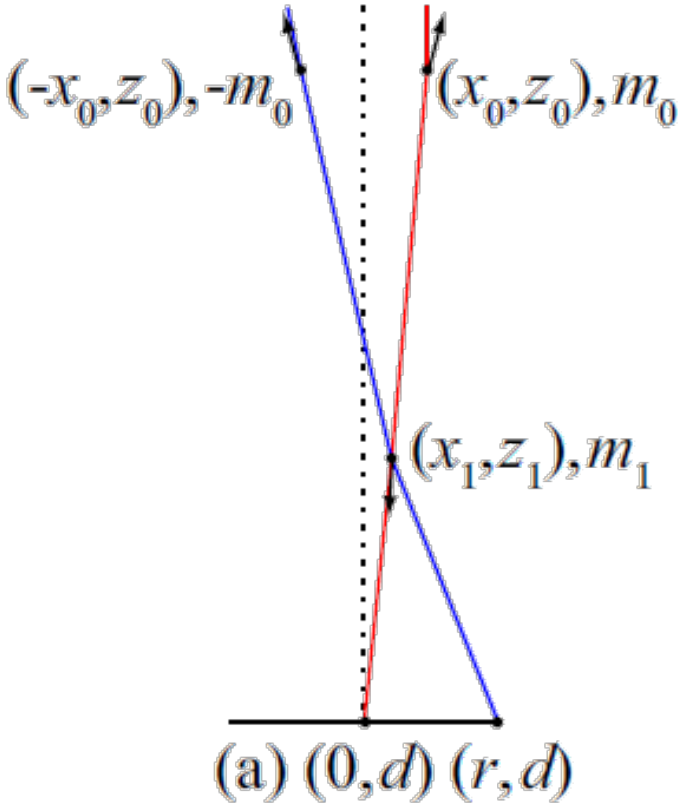
The two off-axis bundles cover the second surface exactly $\longrightarrow$ Surface = 2 x beam print

F. Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Optics Express Vol. 20, No. 5, 2012

Unique analytic solution exits

Two surfaces, three object points





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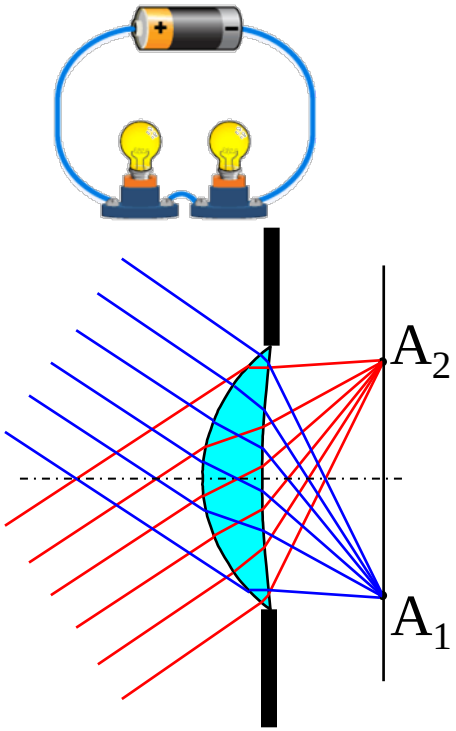
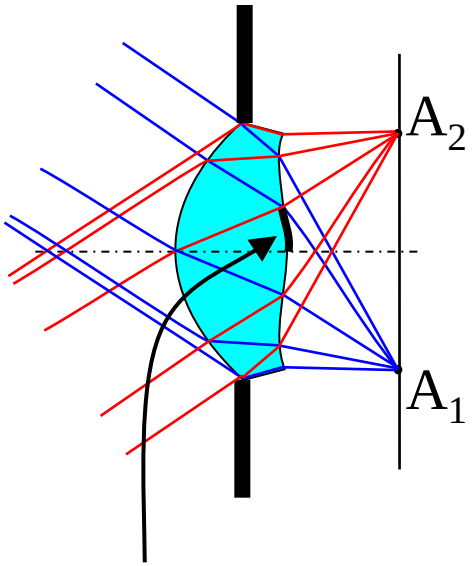
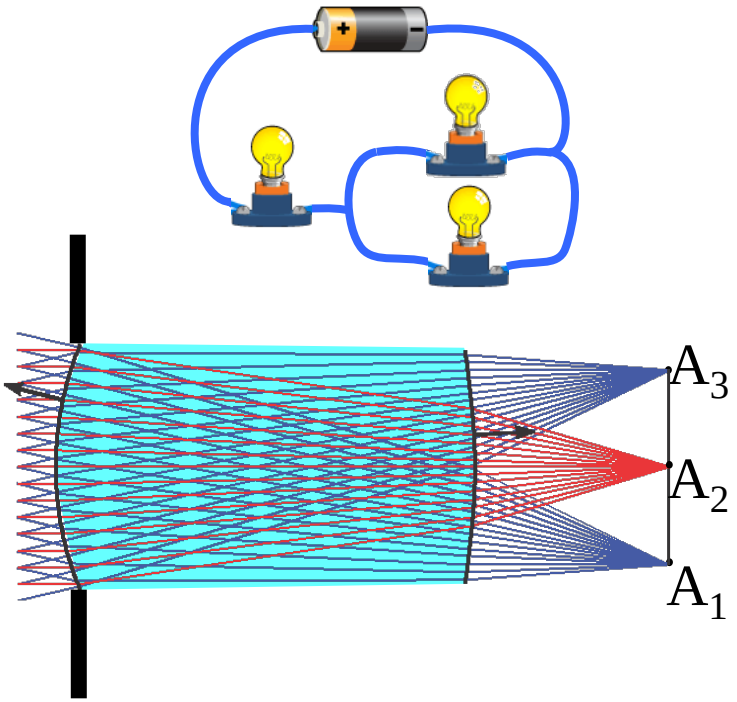






Unique solution

Free patch

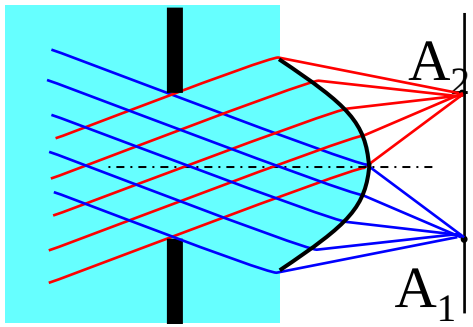
Unique solution

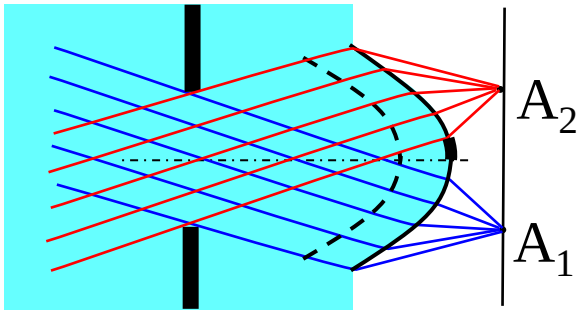
Two object points

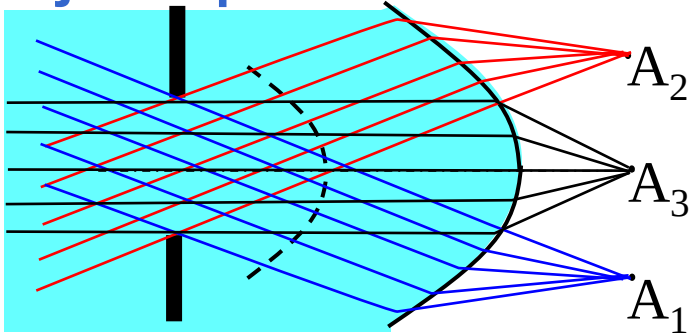
Three object points

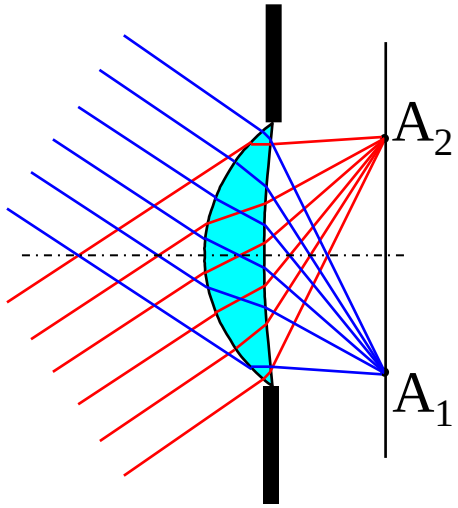
P. Benítez, J.C. Miñano, M. Nikolic,
L. Jiayao , J.M. Infante, F. Duerr

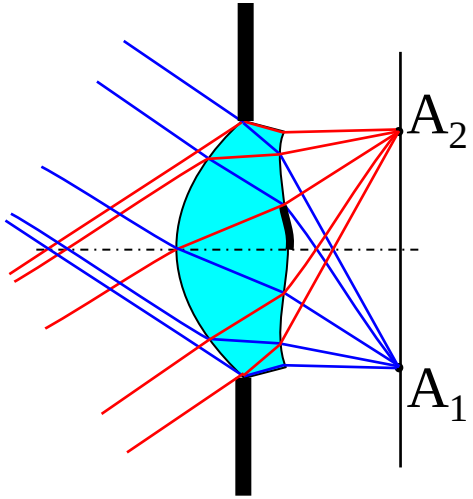
Transition from two to three object points

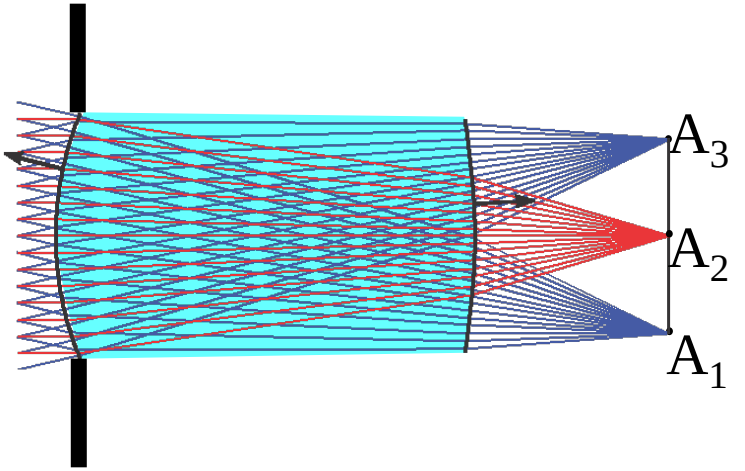












Unique solution

Free patch

Two object points

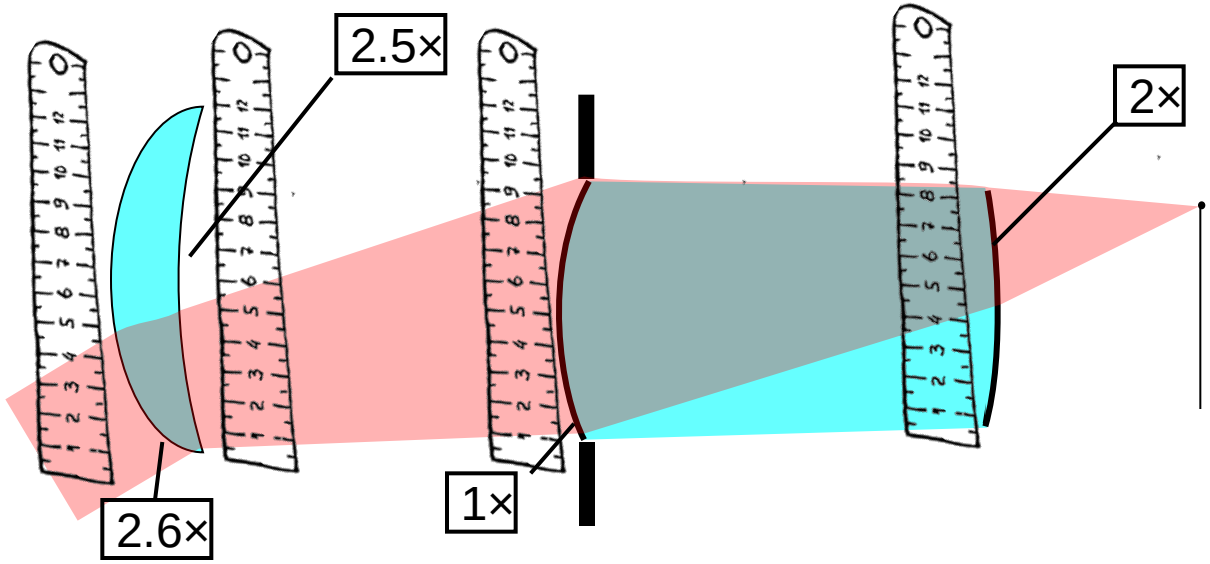
Unique solution

Three object points

P. Benítez, J.C. Miñano, M. Nikolic,
L. Jiayao , J.M. Infante, F. Duerr
OSA Freeform meeting, November 2013

General rule of thumb

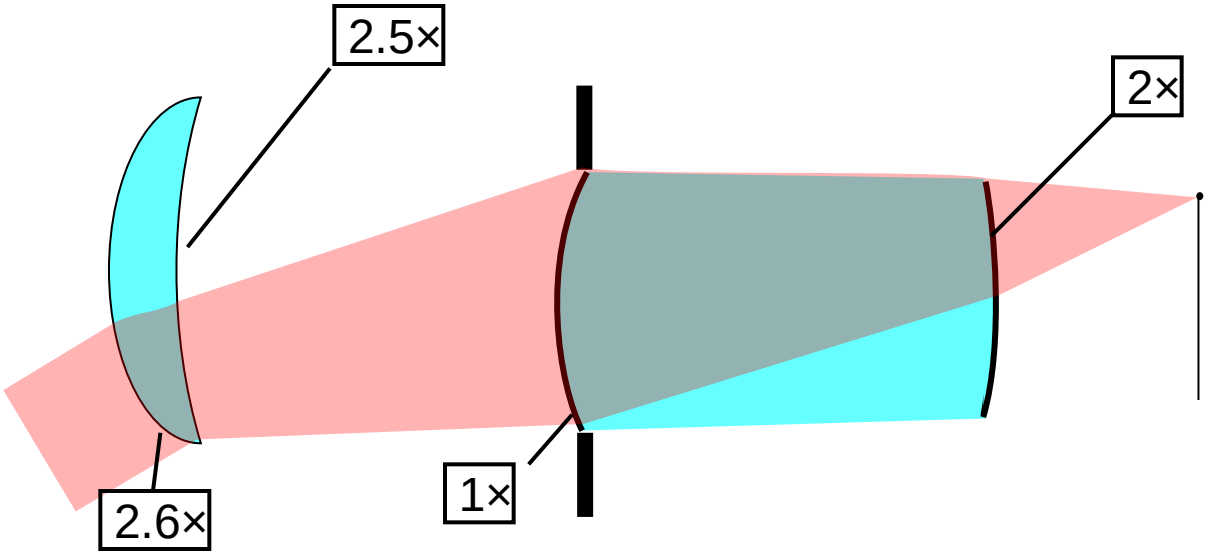
$$\text{Number of object points} \leq \sum E \left(\frac{\text{Extension of surface}}{\text{Extension of beam print}} \right)$$



Number of object points (2D) ≈ 2+2+1+2 = 7

General rule of thumb

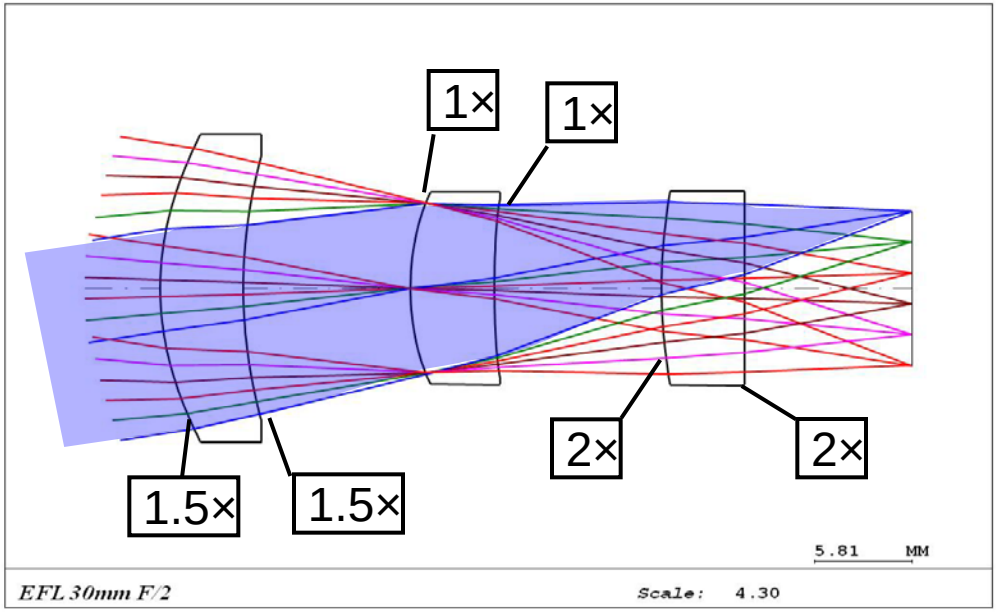
$$\text{Number of object points} \leq \sum \frac{\text{Extension of surface}}{\text{Extension of beam print}}$$

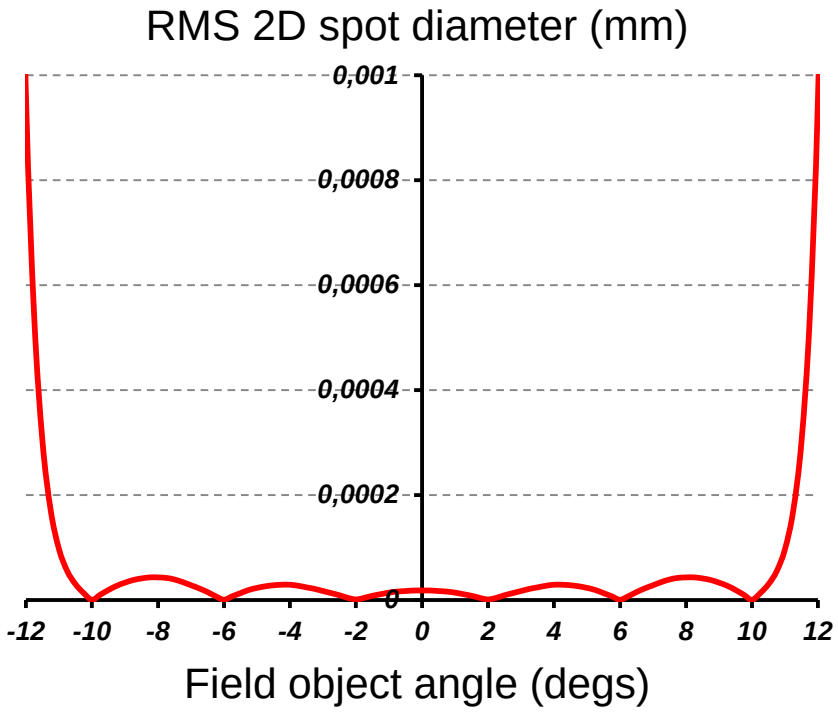


Number of object points (3D; round field) $\approx 2^2+2^2+1^2+2^2 = 13$

Example

First design: 6 surfaces, 6 object points



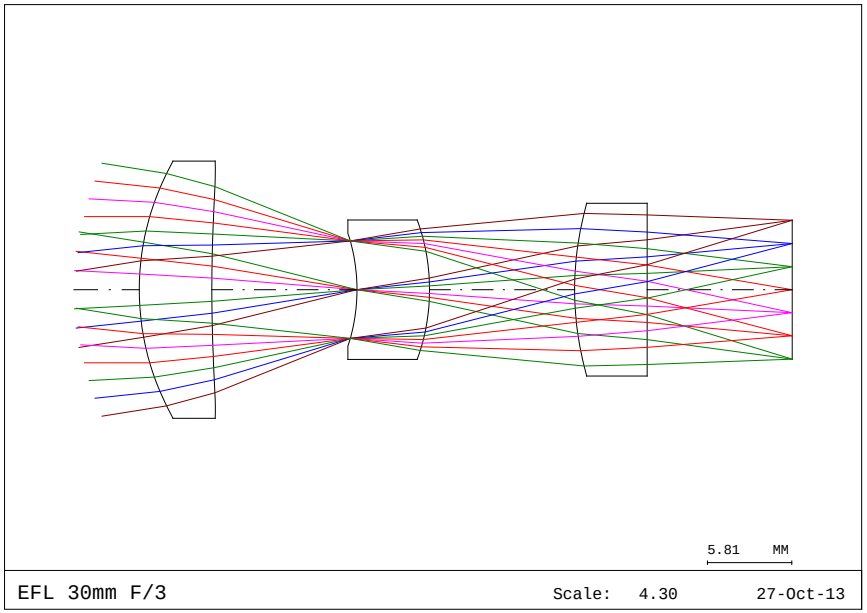


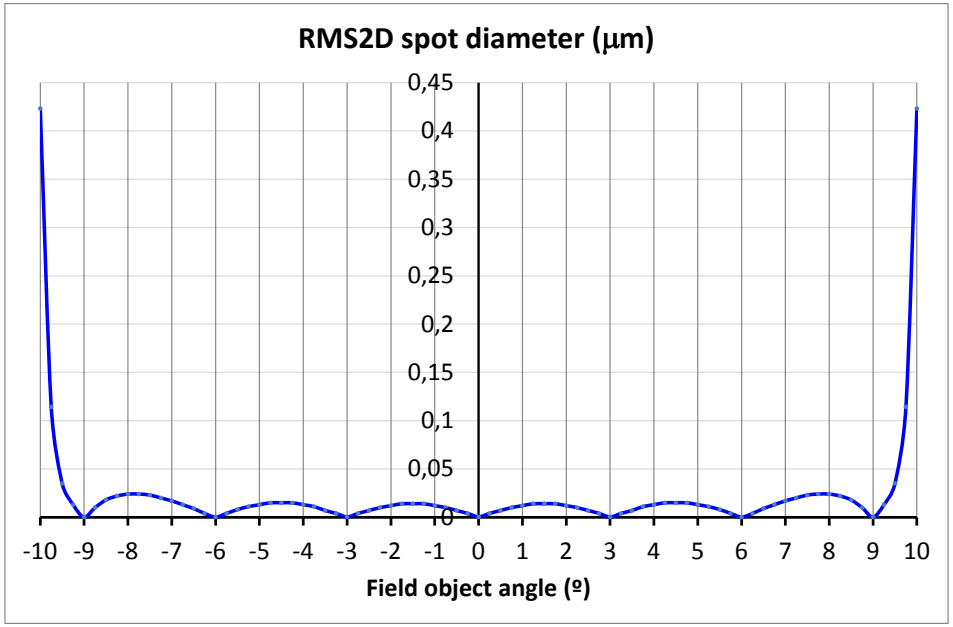
1+1+1+1+2+2 = 8

Jose Infante,PhD dissertation, October 2013

Example

Improved design: 6 surfaces, 7 object points





1+1+1+1+2+2 = 8

Still improvable!
8 zeros should be achievable!

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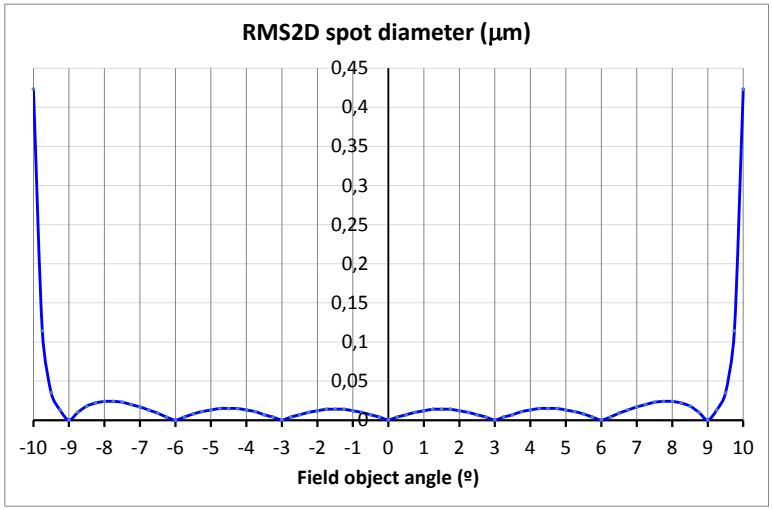
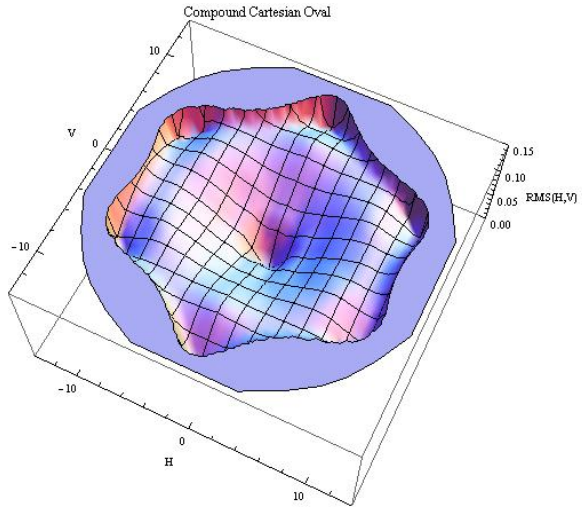
SMS and optimization combination

When maximizing the object points to sharp image, we try to exhaust the degrees of freedom of aspherics and freeforms.



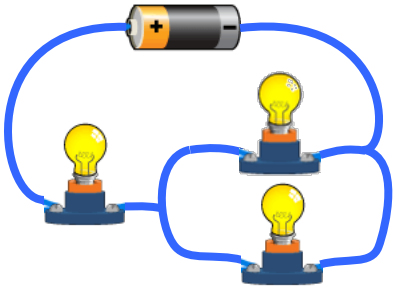


We conjecture that maximal SMS designs are close to a good solution (local minimum)

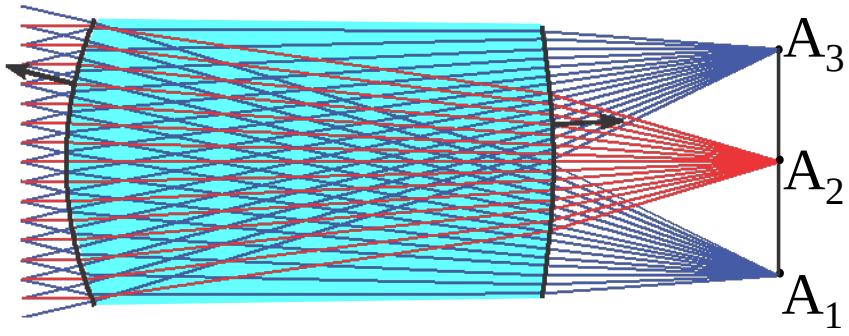
SMS optimization strategies

1. SMS surface can be combined with standard surfaces.
2. The free-parameters of the SMS (vertices positions, free patches, wavefronts) can be optimised.
3. An SMS design can be used as a good starting point for a standard optimization

Example: Imaging with high aspect ratio

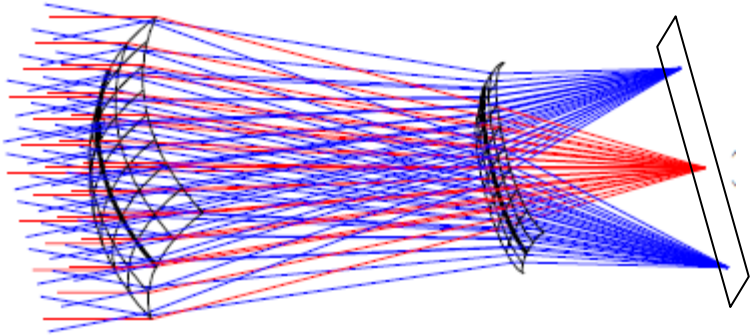


SMS 2D



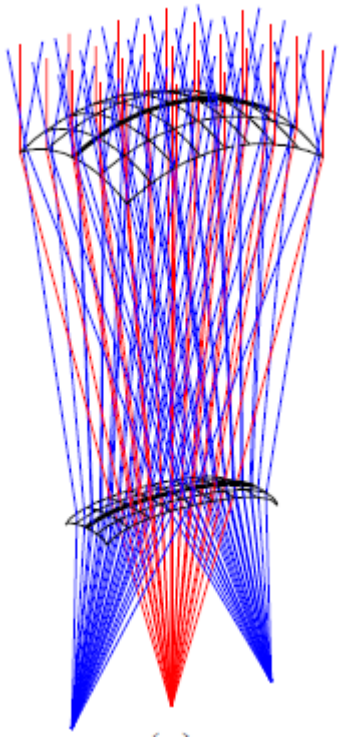
F. Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Opt.Express 20,1 5576–5585, (2012)

SMS 3D

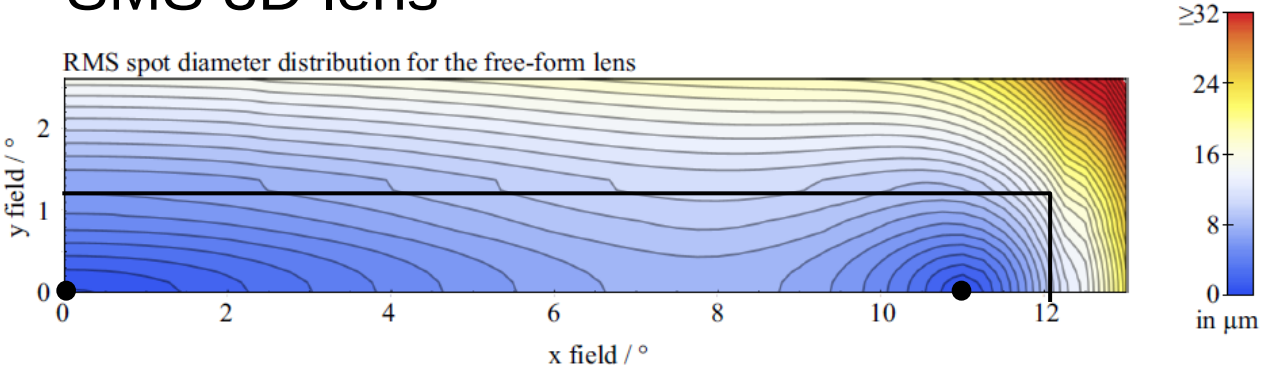


F. Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Optics Express 20, 10839–10846, (2012)

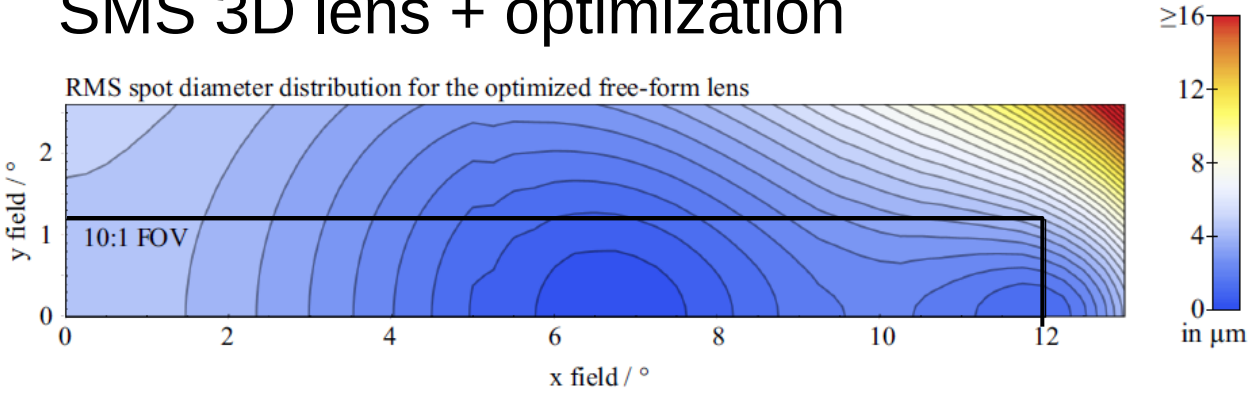
Imaging with high aspect ratio



SMS 3D lens

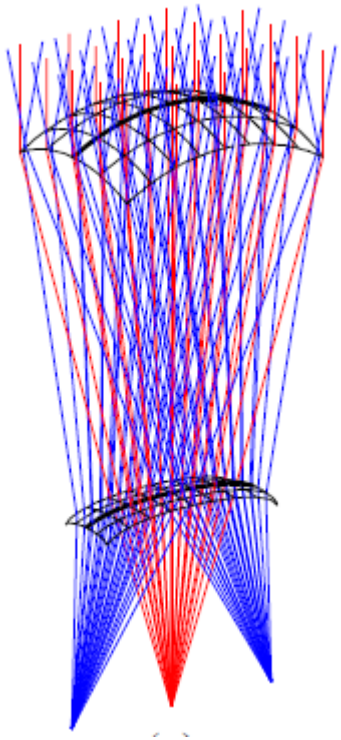


SMS 3D lens + optimization

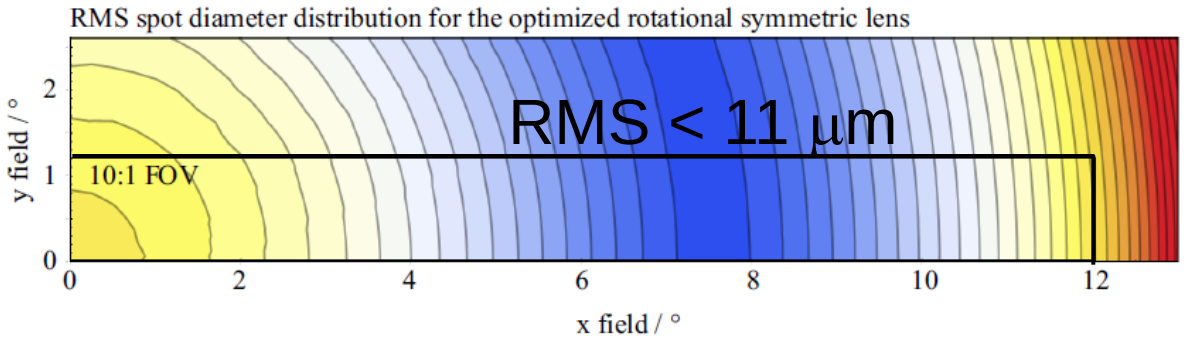


F.Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Optics Express 20, 20,10839–10846 (2012)

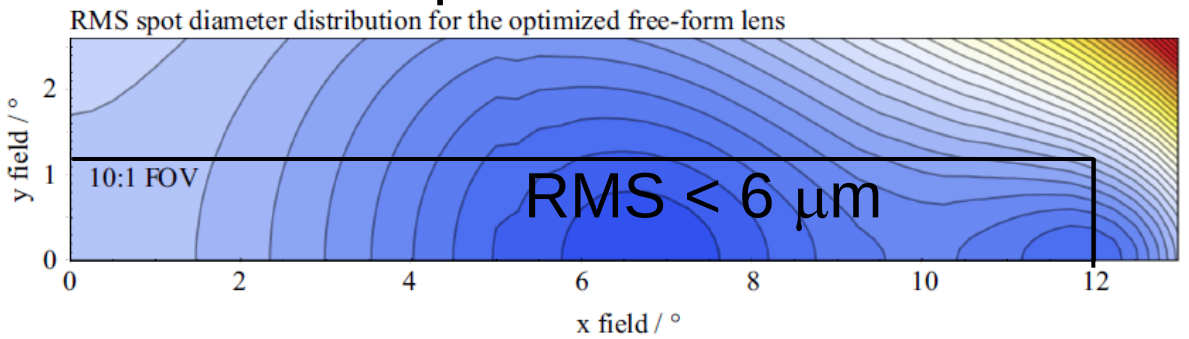
Imaging with high aspect ratio



Optimised rotatonal lens



SMS lens + optimization



F.Duerr, P. Benítez, J.C. Miñano, Y. Meuret, H. Thienpont, Optics Express 20, 20,10839–10846 (2012)

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Conclusions

- Is it possible to sharply image M object points with N surfaces when N < M? Yes!
- Under what conditions? When surfaces are not at the aperture stop.
- Why is it interesting for optimization? You have an good starting point
- What is the role of the SMS method? Provides a direct algorithm to the solution

Acknowledments

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- Synopsys for the academic licence for Code V
- LPI for their support under their Associated Entity Agreement

Thank you!